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ENGINEERING DESIGN HANDBOOK

HARDENING WEAPON SYSTEMS AGAINST RF ENERGY

HEADQUARTERS, U.S. ARMY MATERIEL COMMAND FEBRUARY 1972

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LIST OF SYMBOLS

Symbol	*Quantity*
A	= ampere
A	= absorption loss; attenuation
Ae	= effective aperture
Aec	= composite effective aperture
Aem	= maximum aperture
AM	= amplitude modulation
Ar	= area
AWG	= American wire gage
a	= semi-major axis of an ellipse
ac	= alternating current
$\bar{a}_r$	= unit radial vector
B	= magnetic flux density
b	= semi-minor axis of an ellipse
C	= conservative loss parameter
C	= coulomb
Cap.	= capacitance
CW	= continuous wave
c	= speed of light
D	= displacement density; directivity
d	= distance
d_e	= electrode spacing
d_h	= distance (height)
d_s	= distance from stroke where dE/dt_{max} is determined
dB	= decibel
dc	= direct current
dE/dt_{max}	= maximum rate of change of electric field
E	= electric field strength
$\bar{E}$	= electric field, vector
E_{max}	= maximum electric field
EED	= electroexplosive device
EMC	= electromagnetic compatibility
EMI	= electromagnetic interference
EMP	= electromagnetic pulse
EMR	= electromagnetic radiation
ERP	= effective radiated power
e	= constant (2.718...), base of natural logarithms
e	= eccentricity
F	= farad
$\bar{F}$	= force
°F	= degrees Fahrenheit
FET	= field-effect transistor
FM	= frequency modulation
f	= frequency
f_{MHz}	= frequency in megahertz
ft	= foot
G	= conductance; antenna gain
G_R	= relative conductivity
GHz	= gigahertz
H	= henry
$\bar{H}$	= magnetic field
Hg	= mercury
Hz	= hertz
I	= current
IL	= insertion loss
I_{max}	= maximum current
I_o	= main stroke current
I_s	= surface current
i	= surface current
in.	= inch
J	= joule
j	= unit imaginary number $\sqrt{-1}$
°K	= degrees Kelvin
kVA	= kilovolt ampere
k	= constant
k_1	= constant (9×10^9)
kA	= kiloampere
kHz	= kilohertz
kV	= kilovolt
kW	= kilowatt
kΩ	= kilohm
L	= inductance
ℓ	= antenna length
ℓn	= natural logarithm
lb	= pound
log	= logarithm to the base ten
MHz	= megahertz
m	= meter
mil	= one thousandth of an inch
mJ	= millijoule
MKS	= meter-kilogram-second

MΩ = megohm
mm = millimeter
MOS = metal-oxide semiconductor
MOSFET = metal-oxide semiconductor field-effect transistor
msec = millisecond
mW = milliwatt
N = newton
n = number
P = power
P_d = power arriving (delivered) at input of RF supression device
P_s = power that gets through system being protected
P_i = incident power
P_r = reflected power
P_{R1} = received power without shield between transmitter and receiver
P_{R2} = received power inside metallic enclosure
P_T = transmitter power
PD = power density
PD_i = incident power density
PD_s = shielded volume power density
pF = picofarad
Q = charge; quality factor
Q_R = figure of merit
R = resistance; reflection loss
R_A = antenna resistance
R_e = real part
R_g = ground resistance
R_L = load resistance
R_m = mutual resistance
R_R = radiation resistance
R_T = termination resistance
$Re(Z)$ = real part of impedance
RF = radio frequency
RFI = radio frequency interference
r = radial distance; radius
rms = root-mean-square
S_{eff} = shielding effectiveness
SE = total shielding effectiveness
SVD = stray voltage detector
sec = second
T = temperature
TEM = transverse electromagnetic
T_c = transmission coefficient
T_p = transmission loss
TV = television
t = time; thickness of shield
t_r = pulse rise time
V = voltage potential
V = volt
V_{max} = maximum potential
V_r = voltage drop across R_g, the ground resistance
v = velocity; speed
W = power
W = watt
Wb = weber
W_{MT} = power transmitted through a solid metal
W_T = power transmitted through a hole
X = reactance
X_A = antenna reactance
X_s = system reactance
X_T = termination reactance
x = shield thickness
x_d = dielectric thickness
yd = yard
Z = impedance
Z_c = cable impedance
Z_d = small dipole radial wave impedance; input impedance of suppression device
Z_{fu} = impedance of firing unit
Z_l = small loop antenna radial wave impedance; impedance of EED; impedance associated with a measuring point
Z_o = characteristic impedance or free space impedance (377 Ω)
Z_{pp} = impedance pin-to-pin
Z_{pc} = impedance pins-to-case
Z_s = shield impedance; combined impedance of system being protected
Z_w = wave impedance
Z_w^* = complex conjugate of Z_w

GREEK LETTERS

α = real part of attenuation constant
β = imaginary part (phase constant) of propagation constant
γ = propagation constant of medium
γ_s = function of electrical parameter of a shield
ϵ = permittivity
ϵ_o = free space (air) permittivity
ϵ_s = surrounding medium permittivity
κ = relative dielectric constant

λ = wavelength
θ = plane angle
π = pi (3.14159...)
ρ = resistivity
ρ_p = power reflection coefficient
σ = conductivity
τ = time from leading edge of field to time of interest; transmission coefficient
μ = permeability; micro
μA = microampere
μ_o = free space (air) permeability
μ_R = relative permeability
μsec = microsecond
μW = microwatt
Ω = ohm
ω = angular source frequency ($2\pi f$)
---° = degree (plane angle)
°C = degrees Centigrade

PREFACE

The Engineering Design Handbook Series of the Army Materiel Command is a coordinated series of handbooks containing basic information and fundamental data useful in the design and development of Army materiel and systems. The handbooks are authoritative reference books of practical information and quantitative facts helpful in the design and development of Army materiel. The purpose of this particular handbook is to take the wealth of information accumulated by the Army over a period of years on the subject of hardening weapon systems against RF energy and to make this information available to the designer. Much of the data in this handbook is in chart or table form for rapid retrieval. Also, references are given that specify where these data were obtained.

Although this handbook was prepared for the designer of weapon systems it should also be of benefit to those engaged in designing test programs for determining the hardening of weapon systems. Chapter 5 presents the latest programming concepts that the Army is now using.

This handbook was prepared by the The Franklin Institute, Philadelphia, Pa., for the Engineering Handbook Office of Duke University, prime contractor to the Army Materiel Command, with Mr. Roy Wood as the principal author. Technical guidance and coordination were provided by a committee with representatives from Picatinny Arsenal, The U.S. Army Electronics Command, Redstone Arsenal, Harry Diamond Laboratories, and White Sands Missile Range. Members of this committee were Mr. Daniel Carella, Chairman, Mr. Edward Ramos, Mr. Francis Wilhelm, and Mr. D. Roger Wight.

The Engineering Design Handbooks fall into two basic categories, those approved for release and sale, and those classified for security reasons. The Army Materiel Command policy is to release these Engineering Design Handbooks to other DOD activities and their contractors and other Government agencies in accordance with current Army Regulation 70-31, dated 9 September 1966. It will be noted that the majority of these Handbooks can be obtained from the National Technical Information Service (NTIS). Procedures for acquiring these Handbooks follow:

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US Army Materiel Command
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CHAPTER 1

INTRODUCTION

1-1 PURPOSE AND SCOPE

The components used for control, timing, sensing, initiation, and other functions in most of the modern weapon systems are electrical in nature. Power to operate the systems is supplied from electric sources, and the explosive components which are used to perform a multitude of functions are electroexplosive devices (EED's); i.e., they are electrically initiated. While many advantages have been gained by the use of these systems, EED's are susceptible to malfunction and degradation as a result of spurious electric signals if the systems and components are not properly protected.

The combined natural and man-made environment which can serve as a source of these spurious signals is at an all-time high and is still increasing. As a result, the engineer designing a weapon system must not only consider the effects of such natural phenomena as lightning and electrostatic charge, but also man-made electric sources such as unwanted circuit transients and radio frequency energy originating from communication equipment, radars, transmitters associated with weapon systems, and nuclear explosions.

It must be kept in mind that the technology is continually increasing the number and power of energy sources, and weapon systems are using more components which may result in more critical hazardous conditions. The engineer responsible for the RF hardening of a system must be continually on guard–from the design stage, through construction and finally deployment–to be certain that he is aware of all facets which affect his system and its probable environment so that proper application of the basic hardening concepts may be assured at all stages of development. It is the purpose of this text to supply the necessary basic concepts.

The electrical portions of modern weapon systems–from very small, compact modules to systems with long, complex runs of wires and cables–are subject to the effects of the natural and man-made electrical environment in which the system must operate or will experience during storage and transportation. Furthermore, structural members and other components not specifically part of the electrical system can become part of the system with respect to extracting energy from an incident RF field or providing a path for electrostatic discharge.

System effects produced by these electrical environments can vary from partial failures of components resulting in changes in their characteristics so that they no longer function properly at their design levels, to complete dudding of components resulting in a failure to operate under any conditions. In the case of the EED it is possible to have premature initiation, frequently resulting in cataclysmic failure of the system. Furthermore, failures may be produced by spurious signals appearing in portions of the components not considered part of the normal electrical path. For example, a hot wire EED specifically designed to be initiated by the dissipation of electrical energy in its bridgewire may be prematurely initiated by a spurious electrical signal appearing between the bridgewire pins and the case of the device.

The electrical environments discussed in this handbook will include the natural environments of lightning and static electricity, and the man-made environment of RF energy. The text will not consider the electromagnetic pulse (EMP) environment of nuclear weapons (see par. 2-4).

In summary, the scope of the handbook will encompass:

a. A description of the environmental electrical energy sources and the mechanisms by which these sources may be coupled into weapon systems, and the resultant effects of such coupling on systems and components

b. Design techniques and practices required to minimize the effects of these sources, including concepts to be incorporated in the original system design

and concepts which can be used in systems already designed and constructed

c. Test methods, equipment, and analytical techniques for determining the possible susceptibility of systems and the effectiveness of a corrective or preventive technique

d. Specific component information pertinent to the overall problem

e. Army or other military facilities available for the required testing

f. Discussion of pertinent Military Specifications.

1-2 EFFECTS OF RADIO FREQUENCY ENERGY

Radio frequency energy, once it has been coupled into a weapon system, can behave in a variety of ways. In general, components susceptible to damage by electric energy fail or are degraded by one of two effects: (1) the component can be subjected to generalized overheating due to too much power dissipation in the unit, or (2) rupture or extreme localized heating can be caused by electric breakdown in the component. The first effect is characterized normally by low voltages and high currents, and the second effect by high voltages and low currents at least before the breakdown. Either effect can result in dudding of the component or complete destruction depending on the magnitude and form of the spurious signal and the sensitivity of the component. In the case of electroexplosive devices premature initiation can result.

Unfortunately, a typical radio frequency (RF) signal can produce both effects in different parts of the same component, depending upon the complex electrical impedance the signal "looks" into. Furthermore, RF is frequently delivered in a manner not usually occurring with dc; for example, many radars deliver their RF energy in short, repetitive pulses. These repetitive pulses have the capability of producing extremely large instantaneous RF voltages that place large electric stresses in different parts of the components. In addition, since the pulses are repetitive, their effects can be cumulative resulting in thermal stacking, progressive breakdown, and other complex damage mechanisms.

Thermal stacking refers to the condition that exists when a region of a component heated by one pulse of a series of pulses is unable to lose all of its heat before the next pulse arrives. As a result each successive pulse raises (stacks) the temperature of the region to a higher value than that produced by the preceding pulse. Therefore, while a single pulse may not be sufficient to damage a component, a repetitive series of pulses may raise the temperature sufficiently to cause degradation or destruction of the component.

In addition to these destructive effects on components, the designer must also consider RF problems which are usually lumped under the heading of radio frequency interference or electromagnetic interference phenomena (RFI/EMI). These signals which may be of a magnitude much lower than the component destroying magnitude are coupled into the weapon system by the same coupling mechanisms and can produce misinformation from telemetering systems, faulty switching, and faulty transmitting.

As an example of the variable effects which can be produced by an RF signal, depending on the impedance into which it is operating, consider a typical case that occurs for many EED's for signals in the region of 1.5 MHz. Such RF energy arriving on the bridgewire leads of the EED would, in general, proceed to heat the bridgewire in much the same manner as a dc signal. The voltage would tend to be low, the RF current reasonably large, and the RF power required to initiate the EED would be quite comparable to the dc power required for initiation. If the incident energy arrived between the pins and the case of the EED, a quite different situation would prevail. Typical pins-to-case impedances at this frequency have a small resistive part and a large reactive part. As a result, rather small incident RF powers can produce large RF voltages across the impedance (resistive and reactive parts) resulting in possible electric breakdown between the pins and the case. As an example, a typical value of pins-to-case impedance Z at 1.5 MHz is

$$Z = 500 - j10000 \ \Omega \tag{1-1}$$

The conductance G for this impedance would be

$$G = 5 \ \mu\text{mhos}$$

If an RF power P of 500 mW was applied to this impedance, the voltage V appearing across the impedance would be given by

$$V = \sqrt{\frac{P}{G}} = 316 \ \text{V} \tag{1-2}$$

a value sufficient to initiate many EED's.

In summary, damage to components due to RF energy occurs in the same manner as it does when the energy is supplied from a dc pulse. However, determining the actual levels which would produce damage is frequently very difficult. Measurement of RF current or voltage is often of little value unless the impedance is known at the same point. Determination of the impedance at the exact point of interest is usually very difficult particularly at high frequencies. As a result, it

is frequently necessary to use an empirical approach to establish the sensitivity of a component to RF energy. As a general rule, however, those failure modes that exist for dc also exist for RF; furthermore, all modes, normal and otherwise, must be considered.

In this handbook the part of the electromagnetic spectrum which is normally considered when discussing the interaction of RF energy and weapon systems lies between 10 kHz and 40 GHz. Here RF energy is produced by AM, FM, and TV transmitters; mobile transmitters; communication gear; radars; diathermy equipment, RF heaters, and other sources. In short, the present environment is produced by many different types of RF sources. Furthermore, modern weapon systems frequently have their own family of RF emitters associated with them and these are in close proximity to the system. The number and power of such sources are increasing, and it is imperative that present and future weapon systems be hardened against the environment they create.

1-3 EFFECTS OF STATIC ELECTRICITY

While this text is primarily concerned with hardening weapon systems and their associated components against RF, the problem of hardening against electrostatic hazards is so closely related that it is convenient to include some discussion of this problem, also. The electrostatic hazard can be characterized as primarily a high voltage, low current breakdown phenomenon; and while frequency components can be assigned to the electrostatic discharge pulse, the breakdown is more closely related to the capacitor discharge pulse than to normal RF sources. However, the electrostatic discharge damages components in the same modes as RF energy and is particularly equivalent to high frequency radar pulses in terms of damage. The controlling circuit parameter is the dc resistance, however, rather than the complex impedance as in the case of RF. Many of the techniques for hardening a system against RF are directly applicable to static electricity.

Electric charges are transferred whenever two masses contact, particularly when the masses are nonconductors. Multiple contact, such as created by rubbing or particle impact on a surface, can greatly increase this charge transfer. Furthermore, a charged body need only approach a second body to cause a redistribution of the charge in the second body. If some path, such as a momentary ground connection, is provided to remove or add charge to the second body, a residual charge will remain on the second body. Examples of these charge mechanisms are easy to find in modern weapon systems. A projectile passing through rain or dust, a plastic cover removed suddenly from a weapon, or the mere presence of a highly charged thunderhead all can provide common methods of producing a charge buildup in components of a weapon system. Any contact or rupture of insulation between a charged body and an EED or circuit component will result in an electric discharge through the component, which may have disastrous results. One fatal accident was traced to EED ignition caused by the electrostatic discharge created during the removal of a plastic shroud from a missile (see par. 2-2.3(c) for the mechanics of this phenomenon).

1-4 EFFECTS OF LIGHTNING

Lightning is a specialized case of an RF source of very high magnitudes. The magnitudes are so great as to make most hardening techniques almost useless when a direct strike on the system occurs. However, a properly shielded and grounded weapon system could survive a direct strike. Fortunately, direct strikes are extremely rare and therefore are not of main concern. Near strikes, however, are a frequent reality. In a near strike the lightning stroke generates an RF signal in a limited frequency range and it is of reasonably predictable duration. This RF signal can be treated in the same manner as that from any other RF source and will damage components in the same manner.

Due to the enormous energies involved, two other mechanisms must be considered when dealing with the problem of hardening systems against lightning:

(1) In the lightning stroke process, enormous charge displacements occur in clouds or bodies on the ground. These charge displacements are rearranged rapidly, causing sizable charge movements in the electrical ground. This large scale movement of charge in and around a weapon system can cause large dc currents to flow in the system circuits and produce considerable damage.

(2) The stroke itself carries a huge current which will in turn produce a strong magnetic field around the conductive path formed by the stroke. The action of such strong magnetic fields penetrates the usual electromagnetic shielding, hence, these fields when coupled through the shielding cause heavy current flow in the system components.

1-5 THE COUPLING OF UNDESIRED ENERGY INTO A WEAPON SYSTEM

Up to this point the discussion has centered on the types of sources that make up the RF environment to which a modern weapon system may be subjected and has indicated how the emission from these sources produces damage to the components of a system. To recapitulate briefly, any voltage or current beyond the normal capacity of a component will, of course, damage the component. In addition, the designer must also be concerned with failure in parts of the components other than those parts where he would expect the normal signal to travel since (1) these other parts are frequently more sensitive than the normal circuit, and (2) it is generally the nature of the spurious signals to attack in all possible failure modes. The manner in which the energy from these sources is coupled into the weapon system will now be discussed.

A modern weapon system consists of an assortment of electrical devices such as power sources, control units, telemetering links, computers, and other units all interconnected by an assortment of cables. The cabling systems contain a large number of wires of considerable lengths and are frequently interrupted with terminal boxes, switches, junctions, and other devices which result in very complex wiring systems. However, in the final analysis, and to the extent that the wiring runs are unshielded, these complex wiring systems break down into a series of smaller loops and shorted parallel wiring runs that differ very little from the dipole, loop, and rhombic antennas that one constructs for the express purpose of extracting RF energy from an incident field. The efficiency of any of these undesired antennas in extracting RF energy from an incident field and transmitting this energy to any of the components in the system is a function of its orientation in the field, the impedance it represents, and its transmission characteristics. These, in turn, are all functions of frequency. The efficiency of the antenna system is also affected by other objects in the vicinity, and by the impedance of the field in the vicinity of this antenna system. In the case of electrostatic energy similar coupling circuits exist, but they may be more subtle.

By now it should be apparent that a precise analysis of any given system with respect to RF, electrostatic, or lightning hazards can be a very difficult and expensive undertaking for all but the simplest systems. The best method to employ is to understand the extent of the RF hazard problem and include in the original design of the ordnance system the proper procedures to harden the system against the expected hazard environment to which it may be subjected. The text which follows provides information to aid the designer in properly evaluating and solving this problem.

CHAPTER 2

SOURCES OF RADIO FREQUENCY ENERGY, STATIC ELECTRICITY, AND LIGHTNING

2-1 RADIO FREQUENCY SOURCES

2-1.1 INTRODUCTION

Many of the modern weapon systems employed by the Army are mobile. This presents a problem since the systems will be subjected to a varying environment that can only be accommodated by an "across-the-board" design against the worst cases likely to be encountered. For fixed installations the protection may be custom-built for the environment encountered at that location but this protection applies only to the particular system configuration at this site and to the specialized assemblies that are used here. Other parts of the system–i.e., those destined for mobile service, although used in the fixed system and perhaps developed under the fixed system concept–should be designed for the usually more rigorous mobile environment. In instances where the fixed environment is expected to exceed the mobile environment, it may be wiser to adhere to the mobile environment for the parts destined for mobile service and employ greater RF protection at the fixed site.

To determine the usual local RF environment of a system, it is necessary to consider the emission from the following three sources:

(1) Civilian RF sources
(2) Military RF sources
(3) Its own RF sources.

2-1.1.1 Civilian RF Sources

The number of communication systems in most civilized countries has increased rapidly during the past few years. TV, FM, AM, mobile, and many other types of communication equipments are spread throughout the country. The number of sources in a given area generally depends upon the population. Near big cities the sources are numerous while in sparsely populated areas the number of sources is fewer. These sources of RF energy must be considered both when a weapon system is in transit or is being installed at a site. Normally the sources occupy the spectrum from kilohertz to gigahertz and may have power outputs of megawatts. It is impossible to list all of the civilian RF sources in this handbook; however, Table 2-1 lists, by frequency, the types of systems in use and the maximum power allowed by the Federal Communication Commission for emitters located in the United States (Ref. 1). From Table 2-1 it can be seen that an emitter at almost any frequency in this part of the spectrum might be encountered by the system.

There are two power classifications contained in Table 2-1: (1) power output of the transmitter, and (2) power output of the transmitter multiplied by the gain of the antenna (Effective Radiated Power).

Table 2-1 lists bands of frequencies rather than specific ones and specifies the maximum power and not necessarily what is being used by a given station. The international stations located in foreign countries usually adhere to the limits set forth in the table; however, local stations can vary. Since the weapon system designer usually must assume that his system is to operate in any part of the world, he is forced to design the system to perform under all expected environments.

2-1.1.2 Military RF Sources

The most hazardous environments probably occur in the vicinity of military installations because the number and type of equipment being used vary from day to day and a high density of emitters can usually be found. Table 2-2 (Ref. 1) lists commonly used RF sources at a typical military installation. This is not a complete listing because classified equipments are omitted.

TABLE 2-1

POWERS VS FREQUENCY FOR NONGOVERNMENT RF SOURCES[1] *

Frequency, MHz	Service	Power, W	Frequency, MHz	Service	Power, W
0.010 - 0.014	Radiodetermination	1,200	8.476 - 8.815	Marine	140,000
0.014 - 0.070	International Fixed Public	50,000	8.815 - 9.500	International Fixed Public	50,000
0.070 - 0.130	Radiodetermination	300,000	9.500 - 9.775	International Broadcast	500,000
0.130 - 0.160	Marine	80,000	9.775 - 11.700	International Fixed Public	50,000
0.160 - 0.200	International Fixed	50,000	11.700 - 11.975	International Broadcast	500,000
0.200 - 0.415	Radiodetermination	1,200	11.975 - 12.714	Marine	8,000
0.415 - 0.510	Marine	40,000	12.714 - 13.200	Marine	140,000
0.510 - 0.535	Government		13.200 - 15.100	International Fixed Public	50,000
0.535 - 1.605	Commercial AM	50,000	15.100 - 15.450	International Broadcast	500,000
1.605 - 1.750	International Fixed Public	50,000	15.450 - 16.460	International Fixed Public	50,000
1.750 - 1.800	Land Mobile	10,000	16.460 - 16.952	Marine	8,000
1.800 - 2.000	Radiodetermination	1,200	16.952 - 17.360	Marine	140,000
2.000 - 2.107	Marine	8,000	17.360 - 17.700	International Fixed Public	50,000
2.107 - 2.850	International Fixed Public	50,000	17.700 - 17.900	International Broadcast	500,000
2.850 - 3.155	Aeronautical	400	17.900 - 21.000	International Fixed Public	50,000
3.155 - 3.400	International Fixed Public	50,000	21.000 - 21.450	Amateur	1,000
3.400 - 3.500	Aeronautical	400	21.450 - 21.750	International Broadcast	500,000
3.500 - 4.000	Amateur	1,000	21.750 - 22.400	International Fixed Public	50,000
4.000 - 4.063	International Fixed Public	50,000	22.400 - 22.720	Marine	54,000
4.063 - 4.238	Marine	8,000	22.720 - 24.990	International Fixed Public	50,000
4.238 - 4.438	Marine	140,000	24.990 - 26.950	Land Mobile	500
4.438 - 5.450	International Fixed Public	50,000	26.950 - 26.960	International Fixed Public	50,000
5.450 - 5.730	Aeronautical	400	26.960 - 29.800	Amateur	1,000
5.730 - 5.950	International Fixed Public	50,000	29.800 - 30.000	International Fixed Public	50,000
5.950 - 6.200	International Broadcast	500,000	30.000 - 32.00	Land Mobile	500
6.200 - 6.525	Marine	140,000	32.00 - 33.00	Government	
6.525 - 7.000	Aeronautical	50	33.00 - 34.00	Land Mobile	500
7.000 - 7.300	Amateur	1,000	34.00 - 35.00	Government	
7.300 - 8.195	International Fixed Public	50,000	35.00 - 36.00	Land Mobile	
8.195 - 8.476	Marine	8,000	36.00 - 37.00	Government	

* Superscript numbers refer to References at the end of each chapter.

TABLE 2-1

POWERS VS FREQUENCY FOR NONGOVERNMENT RF SOURCES[1] (Cont.)

Frequency, MHz	Service	Power, W
37.00 - 38.00	Land Mobile	500
38.00 - 39.00	Government	
39.00 - 40.00	Land Mobile	500
40.00 - 42.00	Government	
42.00 - 50.00	Land Mobile	500
50.00 - 54.00	Amateur	1,000
54.00 - 72.00	Commercial Television	100,000*
72.00 - 74.60	Fixed	500
74.60 - 76.00	Radiodetermination	2,000
76.00 - 108.00	Commercial, TV, FM	100,000*
108.00 - 117.975	Radiodetermination	2,000
117.975 - 114.00	Aeronautical	50
114.00 - 148.00	Amateur	1,000
148.00 - 161.575	Land Mobile	600
161.575 - 161.625	Marine	1,000
161.625 - 174.00	Land Mobile	600
174. - 216.	Commercial	316,000
216. - 225.	Amateur	1,000
225. - 250	Radiodetermination	2,000
250. - 420.	Government	
420. - 450.	Amateur	1,000
450. - 470.	Land Mobile	600
470. - 890.	Commercial Television	5,000,000*
890. - 960.	Fixed	30
960. - 1,215.	Aeronautical	50
1,215. - 1,300.	Amateur	1,000
1,300. - 1,535.	Aeronautical	
1,535. - 1,850.	Government	
1,850. - 2,200.	Fixed	18
2,200. - 2,300.	Government	
2,300. - 2,500.	Amateur	1,000
2,450. - 2,700.	Fixed	12
2,700. - 3,300.	Radiodetermination	
3,300. - 3,500.	Amateur	1,000
3,500. - 3,700.	Government	
3,700. - 4,200	Fixed	100
4,200. - 5,650.	Government	
5,650. - 5,925.	Amateur	1,000
5,925. - 6,425.	Fixed	100
6,425. - 6,575.	Land Mobile	100
6,575. - 6,875.	Fixed	7
6,875. - 7,125.	Land Mobile	100
7,125. - 10,000.	Government	
10,000. - 10,500.	Amateur	1,000
10,500. - 10,550.	Public Safety	40
10,550. - 10,680.	Land Mobile	5
10,680. - 12,200.	Land Mobile & Fixed	
12,200. - 13,250.	Fixed	5
13,250. - 19,400.	Government	
19,400. - 19,700.	Land Mobile & Fixed	5
19,700. - 21,000.	Government	
21,000. - 22,000.	Amateur	1,000
22,000. - 27,525.	Government	
27,525. - 31,300.	Fixed	5
31,300. - 38,600.	Government	
38,600. - 40,000.	Land Mobile & Fixed	5
All Above 40,000.	Amateur	1,000

*Effective Radiated Power

TABLE 2-2

RF SOURCES AT A TYPICAL MILITARY INSTALLATION[1]

Emitter	Frequency, MHz	Input Power, W	Antenna Gain G, dB	ERP*, W
FRT-24	1.8-26	1,000	8	6310
FRC-6	1.8-26	1,000	2	1590
TCS	1.8-26	40	2	63
FRT-15	1.8-26	3,000	2	5770
TCB	1.8-26	400	2	630
TDQ	100-150	25	2	3980
GRT-3	225-390	100	10	1000
GRC-27	225-390	100	10	1000
TED	225-390	50	10	500
AN/GMD-2	225-390	30	10	300
FRW-2	400-500	10,000	15	316×10^3
AN/ARSR-1	1,300	4,000	34	10×10^6
MPS-19	2,600-3,400	200	33	400×10^3
SCR-584	2,700-2,900	300	35	948×10^3
AN/FPS-6A	2,700-2,900	4,500	39	35.7×10^3
VERLORT	2,800	150	28	94.5×10^3
AN-APS-20C	2,800	400	34	1000×10^3
M-33	3,000	1,300	39	10.3×10^6
AN/FPS-68	5,400-5,700	275	40	2.75×10^6
AN/SPS-5	5,400-5,700	285	28	180×10^3
AN/MPS-26	5,400-5,700	80	38	480×10^3
AN/FPS-16	5,500	1,707	44	43×10^7
AN/CPS-9	9,063	1,300	30	1.3×10^6

*ERP = Effective Radiated Power

ERP = Input power × Antenna gain

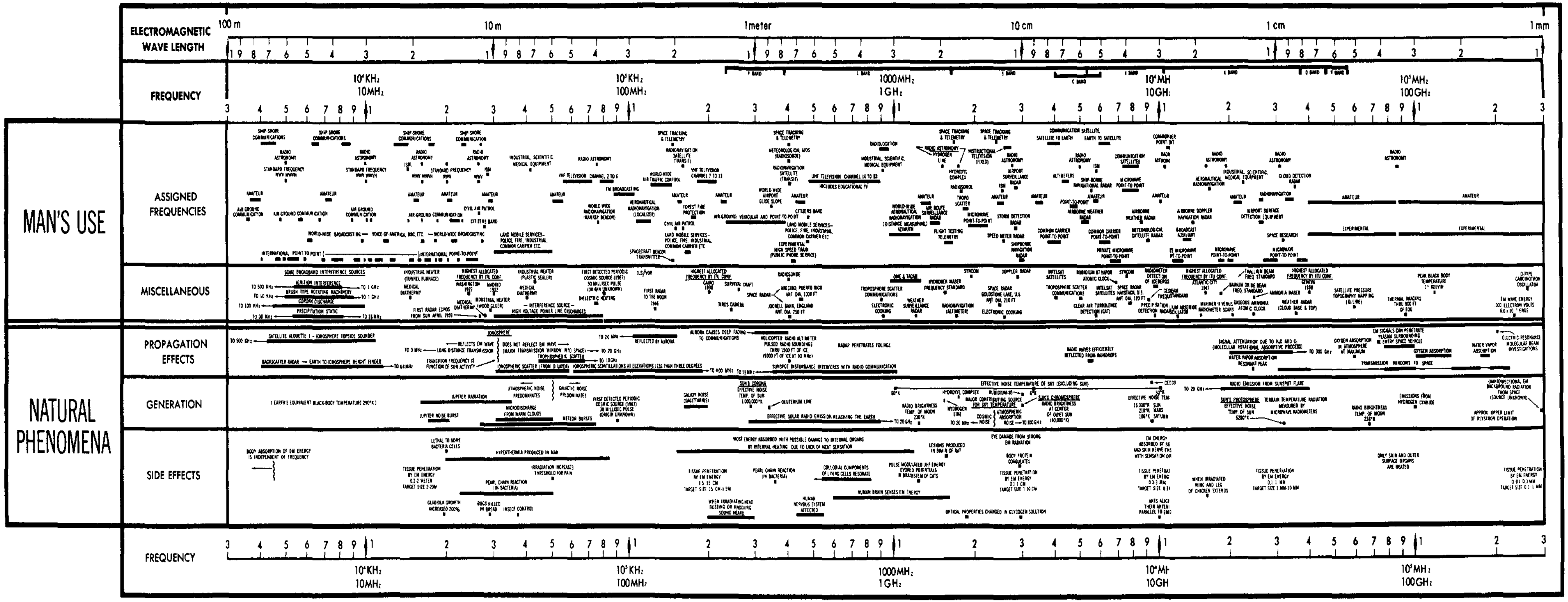

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Fig. 2-1. Frequency Spectrum[3]

2-1.1.3 Weapon System RF Sources

Most Army weapon systems are associated with some form of communication and surveillance equipments. These equipments will normally be the closest RF sources to the system; therefore, it is important that the designer consider the frequencies and power outputs of these equipments so that he may ensure that his system design will be adequate to protect the weapon system against damage or interference at these frequencies.

All military systems that contain electronic equipment must have an RFI/EMI specification. The designer should consult these specifications first to determine the magnitude and the frequencies involved.

2-1.2 ENVIRONMENT

The designer of a weapon system does not have control over the environments that his system will encounter in its use. This includes the physical environment that produces effects as corrosion, shock, heat, etc. It also includes the electrical environment which produces energy in the form of radio frequencies,* static electricity, electromagnetic pulses, and lightning discharges. The information presented in the paragraphs which follow will give the designer of the weapon system some insight into the needs and purposes of the information given on design criteria.

As was pointed out previously, an Army weapon system must be able to operate in any part of the world under all kinds of environmental conditions. Fig. 2-1 indicates the possible types of sources in the frequency spectrum that a system may be exposed to and must be protected against (Ref. 3). The energy that is radiated over this spectrum can create two problems in a weapon system: (1) the energy can be great enough to damage the components or subsystems, or (2) the RF stimulus may interfere with the operation of the system even without damaging components or subsystems. The second condition is referred to as radio frequency interference or electromagnetic interference (RFI/EMI) and is usually with field intensities lower than those which can cause permanent damage to the system.

* One excellent source of information for the weapon system designer seeking to discover the environment (both military and civilian) he may expect in various localities is the Electromagnetic Compatibility Analysis Center located at Annapolis, Maryland (Ref. 2). This center is a joint-service Department of Defense facility, established to provide rapid analysis of electromagnetic compatibility projects of the military departments.

The ideal situation would be to have a chart or a graph that would reveal the expected field intensities a particular weapon system would encounter. The electromagnetic environment that an individual weapon system is required to survive is usually specified in the Qualitative Materiel Requirements (QMR) and Technical Characteristics (TC) for weapon systems requirements.

In Chapter 3, Fig. 3-3 shows the various field intensities that are encountered when RFI/EMI specifications are given. From this information it can be seen that the maximum field intensity specified is 10 V/m. For hardening, the field intensities to be protected against may be as high as several hundred volts per meter.

2-1.2.1 Calculation of RF Environment

a. *General.* In order to determine the RF environment at a given location in a weapon system it is necessary to know the power density or field strength of every signal impinging on that point in the system.

For a directive antenna, the maximum effective radiated power occurs in the center of the beam and is equal to the product of the transmitter power P_T and the antenna gain G.

b. *Power Density.* The power density PD at a distance of d meters from a single radiator is

$$PD = \frac{P_T G}{4\pi d^2}, \text{ W/m}^2 \tag{2-1}$$

The total power density is simply the sum of the individual contributions.

c. *Field Strength.* The field strength contributed by each transmitter can be obtained by recalling that $PD = E^2/Z$ and that the impedance of free space is 120π ohms; therefore,

$$E^2 = \frac{120\pi \; P_T G}{4\pi d^2},$$

or (2-2)

$$E = \frac{5.5(P_T G)^{1/2}}{d}, \text{ V/m}$$

A conservative estimate of the total field strength of n radiators is:

$$E = (E_1^2 + E_1^2 + \ldots + E_n^2)^{1/2} \tag{2-3}$$

2-1.2.2 Radiating Sources (Antennas)

Radio frequency energy that is radiated into space generates electromagnetic waves. These waves are composed of an electric field $\bar{E}$ and a magnetic field $\bar{H}$ where both $\bar{E}$ and $\bar{H}$ are vector quantities (the bar over the letter designates a vector quantity) in that both have direction and magnitude at any point in space. They are perpendicular to each other and to the direction of propagation when located a distance from the source; this is commonly referred to as TEM mode of propagation. The distinction between the fields at a large distance from the radiating source and those near the source is important. Fig. 2-2 illustrates how the region around an antenna is specified. The area outside the circle is called the far field or Fraunhofer region and the area inside the circle is referred to as the near field or Fresnel region. Eqs. 2-1, 2-2, and 2-3 are valid only when applied to measurements made in the far field. Calculation of the field intensity in the near field is very complicated and is seldom attempted. The approximate distance from the antenna to the boundary between the near and far field can be calculated from Eq. 2-4 (Ref. 4)

$$d = \frac{2\ell^2}{\lambda} \qquad (2\text{-}4)$$

where

d = distance from antenna to boundary, m
ℓ = length of antenna, m
λ = wavelength, m

A source that emits radio frequency energy can be considered an antenna regardless of whether it is an intentional antenna or not. The difference usually is that a circuit that is not designed as an antenna will not be very efficient and, accordingly, a poor emitter.

In order to have a method of comparing one radiator to another, the concept of an isotropic antenna was created. In very simple terms an isotropic radiator is an antenna that is a point source that radiates in a spherical pattern. If at a given distance from the point source and with a given input power: (1) a certain power density were measured, and if (2) another antenna were put in place of the isotropic source and the same amount of power applied to it, and (3) the power density at the same point from the source were measured; the ratio of these power densities would be defined as the gain over an isotropic source and would be given in dB of gain.

It would be impossible to make a meaningful list of antenna types since there are so many types in use. The most useful piece of information about an antenna that the weapon system user can obtain is its field pattern. Fig. 2-3 illustrates the two extremes of patterns.

The dipole antenna, with its doughnut-shaped pattern, has the least gain while the parabolic reflector, with its pencil-shaped beam, has the highest gain. In between these two types there are many others. Using Eqs. 2-1, 2-2 and 2-3, the power density and field intensity can be readily calculated if the antenna gain is known.

2-2 STATIC ELECTRICITY

2-2.1 INTRODUCTION

The present understanding of the nature of matter shows it contains equal amounts of and negative

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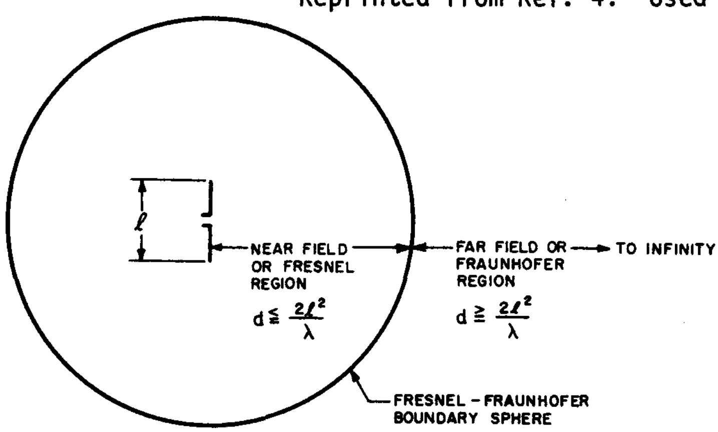


Fig. 2-2. Relationship of Near Field and Far Field

charges, and under ordinary conditions a body thus composed is neutral. There are many ways, however, that the balance between the charges can be distributed to produce an imbalance or a charged body. A rubber rod will become negatively charged when rubbed with fur (Ref. 5). Measurements show that the fur assumes a charge that is exactly equal and opposite to that on the rod. This experiment indicates that a static charge can be generated by the transfer of charged particles from one body to another body.

The generation of a static electric charge on a body by rubbing is called the *triboelectric effect*. Table 2-3 shows an arrangement of nonconductors in what is called a triboelectric series. A substance selected from the series and rubbed with one below it will acquire a positive charge. A conducting material also will assume a positive charge when rubbed since it will give up electrons readily. The conductor must be insulated, however, to prevent other electrons from flowing into it and thus neutralizing the charge.

TABLE 2-3

TRIBOELECTRIC SERIES

(1) Glass	(5) Amber
(2) Wool	(6) Sealing wax
(3) Cat's fur	(7) Sulfur
(4) Silk	

Objects may also be charged by electrostatic induction, i.e., transfer of charge without the objects coming in contact with each other. An example of how this can occur is shown in Fig. 2-4. (A) shows two bodies, one charged and one uncharged, separated by a large distance so that they do not influence each other. In (B) the two bodies are brought into close proximity to each other. Since like charges repel and unlike charges attract, the distribution of the charges on the uncharged object will be altered as shown. Now, if the negative end of the neutral body is grounded (C), electrons will flow into the ground to neutralize the negative charge. Removing the ground connection and separating the two bodies (D), the object that was previously neutral will now be charged positively.

2-2.2 DEFINITIONS

To help the designer avoid designs that are susceptible to static electricity, it is important that the concept of static charges be understood. One way of achieving this is to start by defining certain basic concepts.

(a) *Static Electricity*

In the strict sense of the word, static electricity means electricity that is standing still. It is used to distinguish the effects produced by electrically charged bodies from those produced by heat, chemical action, and magnetic forces which are the results of *dynamic electricity*. In this handbook, the main concern is with static electricity that is the source of a sudden discharge that can activate or damage a circuit.

(b) *Coulomb's Law* (Ref. 6)

The force of attraction or repulsion between two point charges, acting in the direction of a line connecting the charges, is directly proportional to the product of the charges and inversely to the square of the distance between them. The magnitude is given by

$$\bar{F} = k_1 \left(\frac{Q_1 \ Q_2}{d^2} \right), \text{ N} \tag{2-5}$$

where

$\bar{F}$ = force, N
Q_1 and Q_2 = charge, C
d = distance between charges, m
$k_1 = 9 \times 10^9$ for air, m/F
1 newton = 0.224 lb force

(c) *Quantity of Charge*

The unit of charge is the coulomb C which is equivalent to *the point charge which repels an equal charge of the same sign with a force of k_1 newtons when the charges are one meter apart in a vacuum*. The value of k_1 in air may, for most practical purposes, be taken as:

$$k_1 = 9 \times 10^9 \text{ m/F}$$

This definition of a quantity of charge is used when the derivation of the electric field and potential equations is being developed in a logical sequence. The practical unit of quantity of electricity, or charge, is the coulomb; it is the charge delivered by a current of one ampere flowing for one second.

(d) *Electric Field*

An electric field is said to exist at a point if a force of electrical origin is exerted on a charged body placed at the point. The field intensity is a vector quantity $\bar{E}$ having both direction and magnitude in terms of force per unit charge.

$$\bar{E} = \frac{\bar{F}}{Q}, \text{ N/C} \tag{2-6}$$

In practical applications, electric fields are usually produced by charges distributed over a surface rather

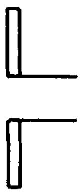
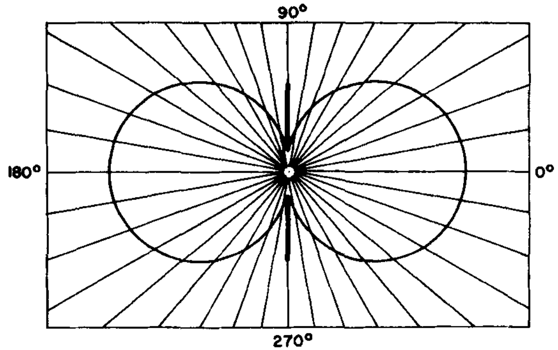
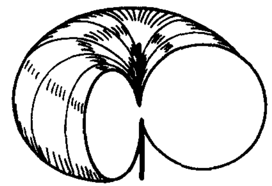
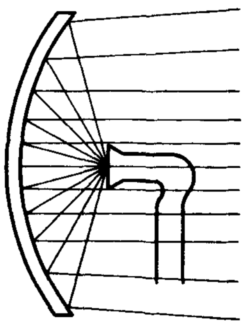
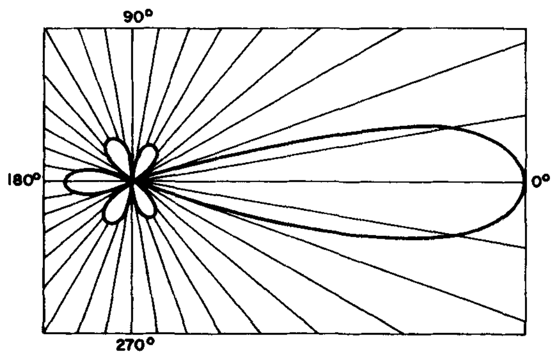
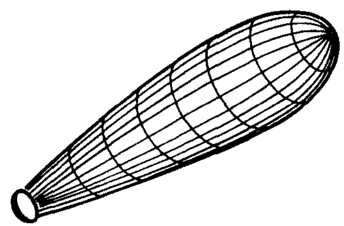
TYPE OF ANTENNA	RADIATION PATTERN		GAIN
	Vertical	Perspective	
Half-Wave Dipole 			1.64
Parabolic Reflector 			20 dB to 50 dB

Fig. 2-3. Antenna Patterns

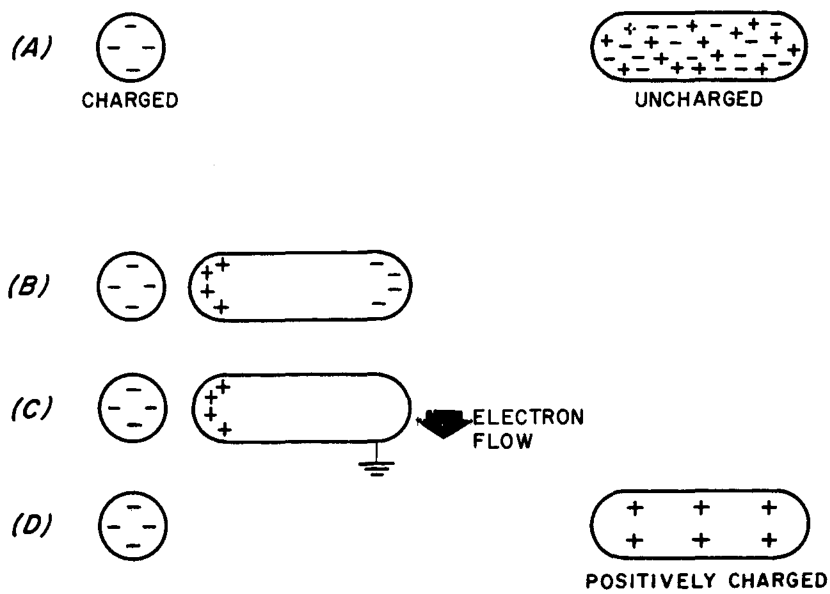


Fig. 2-4. Charging by Induction

than a point source; hence, the vector sum of the charge is used to express the electric field.

$$\bar{E} = k_1 \int \bar{a}_r \frac{dQ}{d^2} \text{, a vector sum, N/C} \quad (2\text{-}7)$$

where

d = distance between the point of interest and charge, m
$\bar{a}_r$ = unit vector in the direction of the field

Expressing $\bar{E}$ in newtons per coulomb is rather awkward; therefore, it is customary to convert to a more practical set of units (Ref. 7). The units that are consistent with the MKS system expresses $\bar{E}$ in volts per meter.

(e) *Potential*

The potential at a point in an electrostatic field is one volt if the ratio of potential energy of a charge at the point to the magnitude of the charge is one joule per coulomb. For distributed charges,

$$V = k_1 \int \frac{dQ}{d} \text{, V} \quad (2\text{-}8)$$

(f) *Maximum Potential*

If the charge on an insulated body were able to build up indefinitely, then the potential would have no upper limit. Fortunately, this is not true. The maximum charge that can be retained by a conductor in air is limited by the fact that the air itself becomes conductive at an electric intensity of about 3×10^6 V/m. The maximum potential that a metallic spherical body in air can achieve is (Ref. 8)

$$V_{max} = rE_{max}\text{, V} \quad (2\text{-}9)$$

where

V_{max} = maximum potential, V
E_{max} = maximum electric field, V/m
r = radius of the sphere, m

2-2.3 THE GENERATION OF STATIC ELECTRICITY

There are many ways to develop a static charge. If these mechanisms are understood, the designer is better equipped to avoid designs which are susceptible to hazards of static charges.

(a) *Friction*

The generation of static electricity by friction (triboelectricity) is probably the most commonly known method. In par. 2-2.1 an elementary example was given of a rubber rod that was rubbed with a piece of fur where both the rod and the fur exhibited equal and opposite charges as a result of rubbing the two together. This principle can be applied on a large scale; as an example, take the case of a vehicle that is hauling a missile system and is equipped with rubber tires. As the vehicle moves over the ground a charge is built up by the rubber tires and deposited on the vehicle. If there is no leakage path to ground, a charge will accumulate until an arc to ground occurs.

Typical of the potentials that can accumulate on a rubber-tired vehicle are those shown in Fig. 2-5 (Ref. 9). The charges are generated by each part of the tread as it leaves the road surface, with a consequent steady build-up in charge. Since it is not possible to completely prevent the static charges due to the friction between tire and surface, the solution is to dissipate the charge. One method is to use rubber tires that are impregnated with a conducting material. This is practical since a resistance of several megohms will bleed off a static charge. A second method is to ground the vehicle. This normally can be done only when the vehicle is stationary. The use of a chain or conductive cloth strap hanging from the vehicle to ground has not proved to be very effective and presently is not employed.

Another example of static build-up occurs on an aircraft flying in a rain storm. The charge that accumulates on the aircraft in this case is the result of two mechanisms: (1) rain rubbing against the metal surfaces and displacing electrons, and (2) the initial charge on the raindrops being transferred to the aircraft surface. Of course, it is not possible to ground the aircraft while it is in flight, therefore, static dissipators are used to prevent large voltages from building up. Static dissipators (Fig. 2-6) are sharp pointed devices that ionize the air around them so that the charge will leak off into the air (Ref. 10). The method by which these devices work is discussed in par. 2-2.4(b).

An Army weapon system that has a severe static electricity problem is the helicopter. The large rotating blades of the rotor make an ideal generator of static electricity. Potentials of up to 1×10^6 V have been measured on helicopters in flight. The energy associated with this potential is about 1 mJ and its discharge may be of sufficient magnitude to ignite fuel or ammunition, cause radio frequency interference, or shock the cargo handler thereby leading to more serious consequences. Any mechanical damage to the helicopter from the static discharge, however, would be insignificant.

The charging rate of helicopters is normally in the range of 40 to 120 μA per second as the rotor of the helicopter rotates in the air. As the charge on the helicopter increases a point will be reached where a corona discharge occurs from one of the sharp surfaces on the helicopter into the air. The energy that emanates from the helicopter as a result of this is usually in discrete bursts rather than a continuous function; hence, radiated interference to radio and navigation equipment occurs. A continuous discharge, or equilibrium, is established when the corona current equals the charging current.

The energy level selected as being nonhazardous to fuel, squibs, and ground personnel for a helicopter is 1 mJ which respresents approximately 1,700 V. In order to reduce the potential on the helicopter to this level, it is necessary to use discharge devices. These discharge devices are rated as one of two types: (1) passive, and (2) forceful.

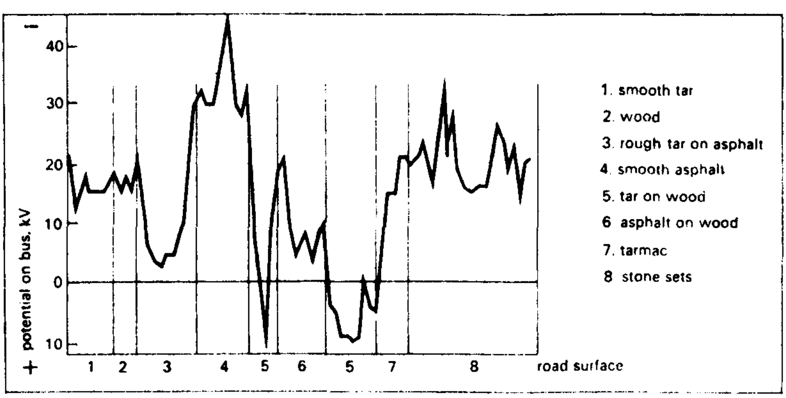


Fig. 2-5. Potential Accumulation on Vehicles With Rubber Tires

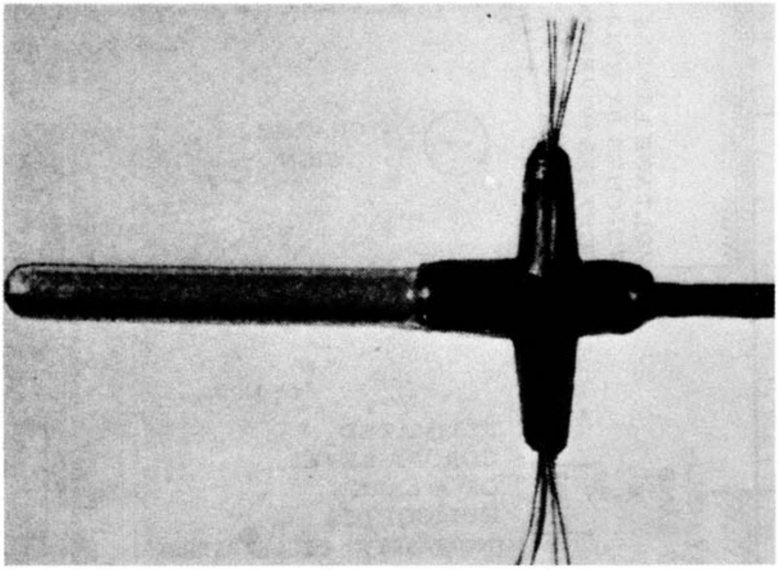


Fig. 2-6. Static Dissipator Used on Aircraft

The passive type of discharger has been discussed in the example of static build-up on aircraft in a rain storm and an illustration of a typical unit of this type is given in Fig. 2-6. Fig. 2-7 shows the static electricity on helicopters and B-707 jet aircraft. From this figure it can be seen that the most effective type of passive discharger lowers the voltage to about 7,000 V which exceeds the level desired.

Corona discharge occurs when the potential at a point ionizes the air around it, thereby allowing the charge on the body to leak into the air. One of the techniques used for a forced or active discharge device is to lower the potential needed to ionize the air around the discharge element. A device now in use places a voltage source between the sharp point of the discharge element and the helicopter skin. This creates a voltage gradient which ionizes the air and permits dissipation of the charge at a low charge level. A peculiar environment where a static charge can readily be generated is the desert environment where the humidity is low and the frictional action of the blowing sand generates a large charge (Ref. 12). Grounding, of course, is desired to prevent the charge from accumulating; however, the dry sandy soil is a poor conductor. This means that ground rods should be driven deeply and the soil soaked with water to obtain good grounds.

(b) *Induction*

The generation of static charge by induction is not as commonly known as the friction method. The mechanism of charging by induction has been discussed in par. 2-2.1 and portrayed in Fig. 2-4. The basic difference between these two methods is that the friction method requires physical contact and the induction method does not. A better understanding of the induction method follows if one recognizes the existence of a static electric force field around a charged body, similar to a magnetic electric field, comprised of lines of force wherein lines of similar polarity repel each other and lines of unlike polarity attract.

When a charged body is brought close to a neutral body, the neutral body is subjected to the electric field of the charged body. If the charged body carries a negative charge, it is carrying an excess of free electrons and the force field of that charge will repel the free electrons in the neutral body forcing them away from the charge. The formerly neutral body is now charged positively nearest the "charging" body and negatively in the portion furthest from the "charging body". The *net* charge on the charged body is still zero and if this body is removed from the influence of the static field the charge on this body will redistribute itself and the body will return to a state of neutral (zero) charge.

An example of how electrostatic induction can affect a weapon is described as follows. Consider a missile in an open area during the passage of a charged cloud. Assume, for the moment, that the missile is insulated from ground by the rubber treads of the launcher. Under these conditions the missile would still be electrically neutral; however, the charges will be redistributed as shown in Fig. 2-8. Now, consider what happens if the launcher supporting the missile is grounded. The excess

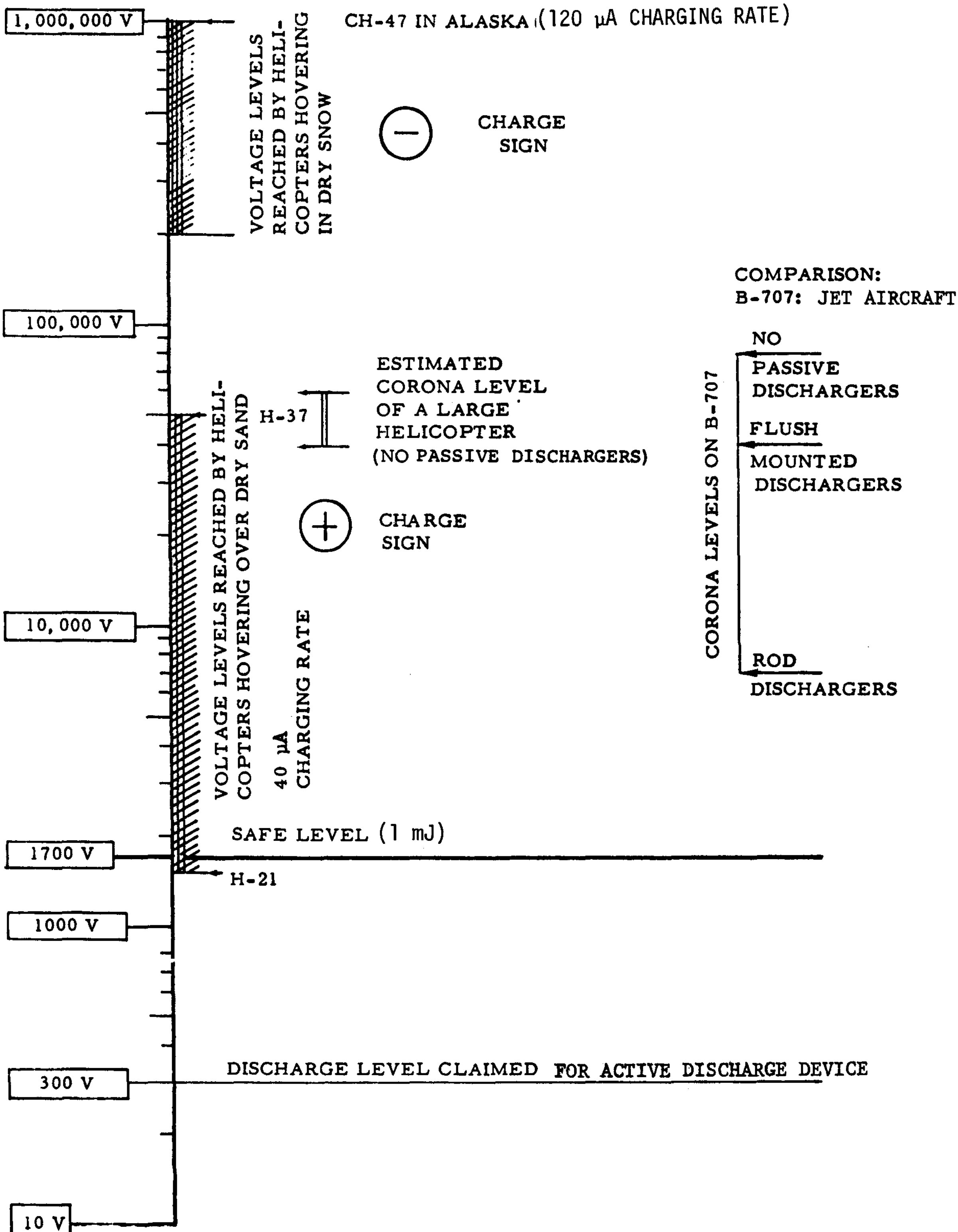


Fig. 2-7. Accumulation of Static Electricity by Helicopters and B-707 Jet Aircraft[11]

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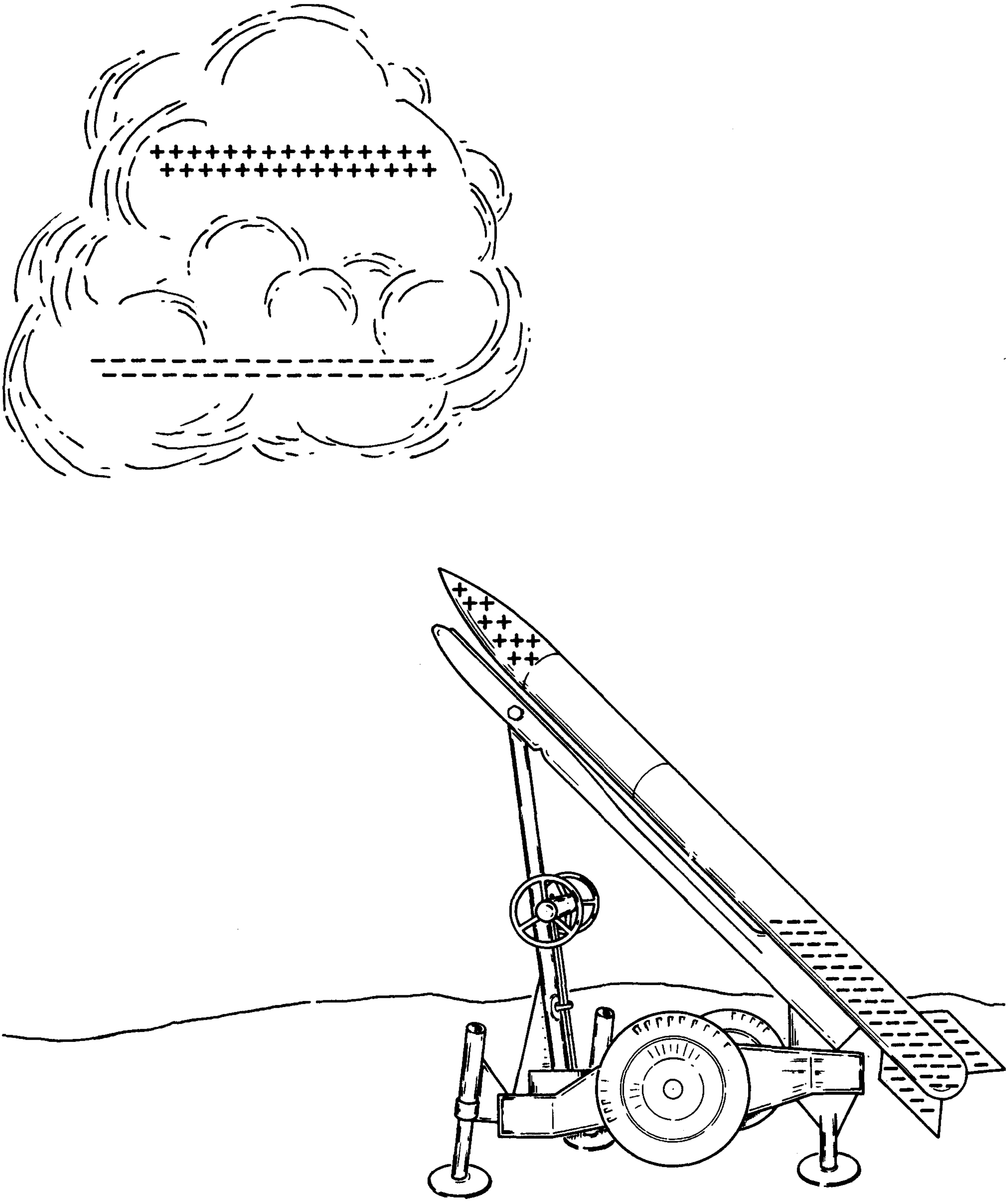

Fig. 2-8. Example of an Induced Charge on an Ungrounded System

electrons will flow into the ground and leave the missile with a positive charge. When the cloud passes, the electrons from the ground will flow back into the missile and neutralize the charge. However, if the ground is removed when the charged cloud is still overhead, the positive charge will remain on the missile even after the cloud has passed because there is no convenient path by which the electrons may return to ground.

Personnel can also induce charges in proportion to the charges that have accumulated on their bodies, but a charge on a human being usually is not sufficient to be of consequence except in certain circumstances where the charge is transferred directly by the skin. An exception to firing by induction occurs in the case of extremely sensitive explosive devices such as conductive mix or carbon bridge detonators (Ref. 13).

(c) *Capacitance and Contact Potential*

If two metal parts of a system are separated from each other by an insulating material, a capacitance will exist between them. Any static charge that builds up on the system will charge this capacitor. Normally the voltages encountered in this situation are not of concern; however, there is a condition whereby the initial voltage can be increased appreciably.

Referring to Eq. 2-10 (Ref. 14),

$$V = \frac{Q}{Cap.} \tag{2-10}$$

where

V = voltage, V
Q = charge, C
$Cap.$ = capacitance, F

it can be seen that the voltage across a capacitor is directly proportional to the stored charge and inversely proportional to the capacitance. Now, if the two metal parts are pulled apart, the capacitance will decrease while the stored charge remains constant. The voltage across the metal parts will vary inversely with the change in capacitance. An example of this is as follows.

If the initial charge on the capacitor is 1×10^{-3} C and the capacitance is 1×10^{-6} F, then the voltage would be 1×10^{3} V. Now, consider the situation when the plates are suddenly pulled apart, decreasing the capacitance to 1×10^{-12} F. Since the charge does not change, the voltage would have to increase to 1×10^{9} V to balance the equation. In actual practice this high potential is not achieved because the air between the plates ionizes and breaks down allowing an arc to form, and thereby redistributes the charge.

This effect actually occurs whenever a missile is released from its launch pad and also when stage separation takes place. The arcs that occur do not cause any physical damage but they do generate RF noises. Proper shielding of the system will prevent this noise from interfering with normal operations.

The same type of voltage generation can occur when two dissimilar metals are in contact and then pulled apart. The different work functions of the two metals will generate a small voltage and when they are pulled apart a small charge will be on each plate. As the distance increases, the voltage will rise.

There are two simplified equations for determining the approximate value of the capacitance between two objects: one for a sphere and the other for two metal plates separated by a dielectric.

(1) For a sphere:

$$Cap. = 1.1 \times 10^{-15}\, r,\ \text{F} \tag{2-11}$$

where

r = radius of the sphere, m

(2) For flat metal plates:

$$Cap. = 8.85\, \kappa \left(\frac{Ar}{x_d}\right) 10^{-12}\ ,\ \text{F} \tag{2-12}$$

where

κ = relative dielectric constant of insulating material
Ar = area of plates, m^2
x_d = thickness of dielectric, m

2-2.4 DESIGN CONSIDERATIONS

The electric field around some simple charge distributions is shown in Table 2-4 (Ref. 15). The entry that is of most importance to the designer is the third one which shows the charge distribution on the surface of a conductive sphere. Although a weapon system rarely ever would be a perfect sphere, the information obtained by using the spherical configuration is considered a good approximation.

A very important piece of design information is contained in Table 2-4. Note that when the *conductive* sphere is charged, the charge appears on the outer surface while on the inside of the sphere the field intensity is zero. This, however, should not be interpreted to mean that the voltage inside the sphere is equal to zero. This is not true. To illustrate this point, consider Fig. 2-9, which shows a charged conductive sphere. The plot directly below the sphere is that of the field intensity, while the one below that is the voltage or potential of the sphere. From these two plots, it can be seen that even though the field intensity inside the conductive sphere is zero, the voltage, referred to ground, is the same on both inside and outside surfaces of the sphere.

TABLE 2-4
ELECTRIC FIELDS AROUND SIMPLE CHARGE DISTRIBUTIONS

Charge Distribution Responsible for the Electric Field	Arbitrary Point in the Electric Field	Magnitude of the Electric Intensity at this Point
(1) Single point charge Q	Distance d from Q	$E = k_1\left[\dfrac{Q}{d^2}\right]$
(2) Single point charges, $Q_1, Q_2, \ldots$	Distance d_1 from Q_1, d_2, from $Q_2, \ldots$	$E = k_1\left(\dfrac{Q_1}{d_1^2} + \dfrac{Q_2}{d_2^2} + \ldots\right)$ (vector sum)
(3) Charge Q uniformly distributed on the surface of a conducting sphere of radius r	(a) Outside, $d > r$ (b) Inside, $d < r$	(a) $E = k_1\left[\dfrac{Q}{d^2}\right]$ (b) $E = 0$
(4) Two equally and oppositely charged conducting plates with charge per unit area D	Any point between plates	$E = \dfrac{D}{\epsilon_o}$

ϵ_o = permittivity of free space
D = charge density

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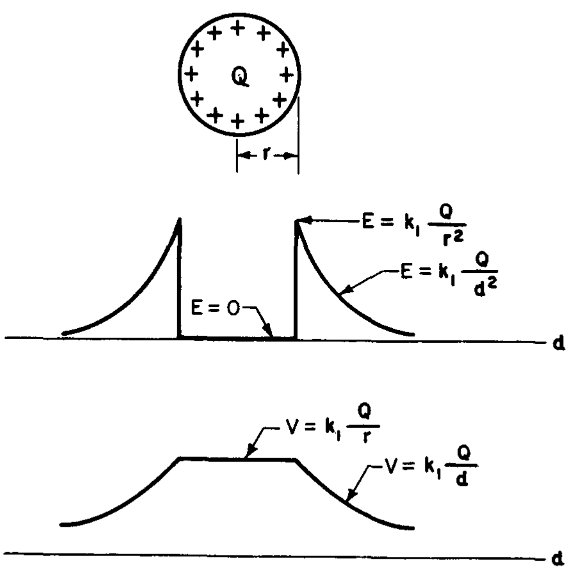


Fig. 2-9. Electrical Intensity E and Potential V at Points Inside and Outside a Charged Spherical Conductor

If the continuous metal skin of a missile is considered as the sphere, then any equipment located inside the missile would not be affected by the static field. Also, since the voltage inside the missile is uniform, the fact that a high voltage from missile to ground exists does not affect the equipment inside the missile. However, if one of the components inside the missile has a return path to ground then there will exist a voltage between that component and ground.

(a) *Effect of Shielding*

Two concepts for protecting the circuits of the weapon system from static electricity are indicated: (1) if the skin of the missile is an unbroken metal surface then the components inside will have protection from an external electrostatic field because no voltage can be induced into them, and (2) if the missile skin is maintained at ground potential there will be very little chance of a charge build-up on the outside of the missile. An exception is shown in Fig. 2-10 where an induced charge can exist on the missile even though the missile is grounded.

(b) *Effect of Shape*

The shape of the missile will influence the amount of charge accumulated on it. The maximum potential that a conductor can exhibit in air is about 3×10^6 V/m because the air itself becomes conductive at this intensity. The formula for the maximum potential to which a sphere can be raised is shown in Eq. 2-9. For example, if a sphere with a 3-m radius is used, then by Eq. 2-9 the maximum voltage that it could attain would be 9×10^6 V. Fortunately, the missiles associated with most weapon systems are not spheres but are more nearly cylindrical in shape with protrusions such as control fins, antennas, vents, etc. The static charge tends to concentrate at the smallest radius on the object. In the case of a missile it could be at the edge of a fin of the missile guidance control system. As an example, suppose the radius of curvature of a control fin is 1 cm, then by Eq. 2-9, the maximum voltage that could be built up on the missile would be 3×10^4 V.

The principle of the smallest radius discharging the static charge is exactly the present system used in aircraft to prevent an electrostatic charge from accumulating during flight. To lower the static potential, several needle-like rods are mounted on the trailing edge of the wing with points having radii of millimeters, this discharges the voltage on the surface of the aircraft to potential of the order of thousands of volts rather than hundreds of thousands of volts. A typical static dissipator is shown in Fig. 2-6. Note the fine wires used to bleed off the charge.

The assumption made in the previous discussion is that the metal skin of the missile is unbroken. If it is assembled from sections that are insulated from each other, the possibility of an unequal charge build-up between sections exists. This can lead to arcing between sections.

(c) *Effect of Separation*

An interesting situation occurs where a static charge can generate a large instantaneous voltage. Consider a missile with a plastic protective cover over it and the cover has some charge. Assume that there is a charge of 100 V on the cover and the cover is removed. The charge on the plastic is referenced to the metal skin of the missile; therefore, the plastic is actually the dielectric of a giant capacitor. The voltage on this capacitor is governed by Eq. 2-10 so that when the cover is pulled away, the capacitance will decrease; however, the charge Q must be conserved according to the principle of the conservation of charge. If the capacitance goes down and Q remains the same, then the voltage must rise correspondingly, to conserve charge. For a plastic cover about 1 mm thick removed 1 m from the missile surface, the voltage would rise by a factor of 1000 or from 100 V to 100,000 V. If the cover were pulled away entirely, the voltage tries to rise to infinity and an arc will occur between the plastic material and the missile skin.

(d) *Effect on Explosive Components*

The sensitivity of electroexplosive devices to static electricity is important since the premature initiation of one of these elements may cause weapon system detonation, and thereby destruction and possible loss of life. It has been demonstrated that sensitive explosive devices can be fired from the electrostatic charge developed by personnel in handling missile components as well as from radiated fields of the weapon system. When selecting the explosive component such as an EED, it is imperative that the designer take into account the possibility of initiation by static electricity.

In par. 4-2 there is a discussion of components used in weapon systems, one of which is the electroexplosive device (EED). The suggestion is made that the designer select EED's from those which have been tested for sensitivity to static electricity. There are several methods employed by the manufacturer of EED's to protect them from static electricity. One method is to place sharp points on the lead wires where they enter the base of the EED to permit any static charge to discharge between these points. A second method is to place a thick insulator between the explosive mix of the EED outer case. The dielectric breakdown voltage of the

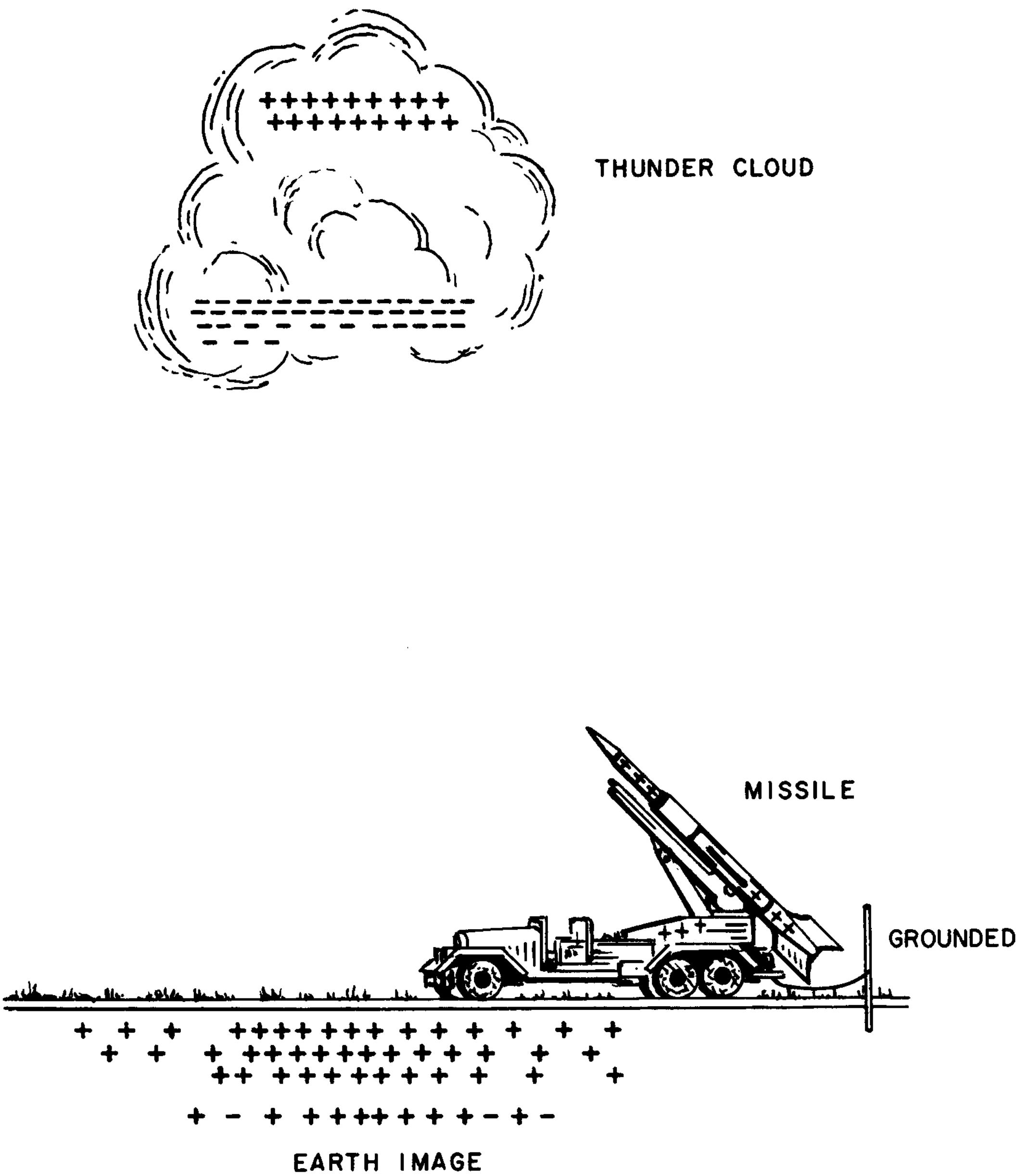


Fig. 2-10. The Static Charge Distribution from Overhead Thunder Cloud on a Missile and Carrier

insulator material should be rated sufficiently high so that the static charge cannot break down the insulator material and arc through the explosive mix. It is not uncommon for an EED of this type to have the ability to withstand 25,000 V from pins-to-case without firing.

A third method employed is to make the plug of the EED conductive so that a static charge cannot accumulate. This, however, presents a problem since some Military Specifications call for the EED to be able to withstand 500 V from pins-to-case from a source capable of delivering high current. At a potential of 500 V, the plugs tend to break down.

Another method for protection from static charge suggested by both the Air Force (Ref. 17) and the Navy (Ref. 18) (not involving the EED directly) is to require that both leads entering the EED have 100,000-ohm resistors between them and ground. The purpose of these two resistors is to bleed off any charge that tends to accumulate between pins-to-case before sufficient voltage can be reached to fire the device.

If this latter approach is used, it should be employed without interrupting the outer shield of the EED circuit. Fig. 2-11 illustrates how the installation of two bleeder resistors may be used in the output side of a safing and arming device.

(e) *Effect on Solid State Circuits*

Solid state circuits such as those consisting of transistors and diodes are very vulnerable to static electricity. These devices are extremely voltage sensitive and are usually limited to low voltage capability. The potentials associated with static electricity are usually high (even though the amount of power available is small) and are sufficiently large to damage transistors and diodes.

One common electrostatic problem encountered with transistor-type components occurs in packaging. Transistors and diodes are normally shipped in plastic bags or cartons. Unless the leads have been tied together prior to packaging, tearing the bag open and pulling out the component will generate a static charge, as discussed in par. 4-3. The charge developed by this operation may be sufficient to burn out the junction of the transistor. Any weapon system circuit that uses solid state devices should be shielded completely so that no charge can be induced into that circuit.

There is no MIL-STD for static electricity tests on EED's; however, MIL-I-23659, *Initiators, Electric, Design and Evaluation of* (Ref. 16), does give the following static requirement:

"3.3.3.2.3 The initiator shall not fire from a 500 micromicrofarad capacitor charged to 25,000 volts when tested as specified in 4.1.4.1."

"4.1.4.1 To determine if the initiator meets the requirements of 3.3.3.2.3, twelve initiators shall be subjected to the following tests. A 500 micromicrofarad $\pm 5\%$ capacitor charged to 25,000 ± 500 volts and a 5000 ohm $\pm 5\%$ resistor shall be connected in series between pairs of pins or leads in all combinations and between the shorted pins or leads (all pins or leads shorted to each other external to the initiator) and the case. Each series connection shall constitute a separate test."

2-3 LIGHTNING

Weapon system components face hazards from five distinct lightning phenomena:

(1) The electrostatic field that exists prior to a lightning stroke

(2) The dynamic electric field that occurs during the leader and main strokes

(3) The dynamic magnetic field that emanates from the main stroke

(4) The electric field that is set up in the earth as a result of the main stroke current

(5) The direct conduction of current from the main stroke.

Lightning discharges are the result of a build-up of static electrical energy in cloud centers. Here the charge is believed to be generated by the breakup of raindrops. Clouds are sometimes positively charged but most frequently they are negatively charged, i.e., their charge appears to be negative with respect to the earth (Ref. 19). The effect, even when the cloud is merely overhead, is one of creating a high intensity electric field at the surface of the earth. Fig. 2-10 shows instantaneous distribution of charge near a grounded missile and its carrier (or launcher) as a storm cloud passes over the site.

As the charge on the cloud accumulates, the potential of the cloud center increases until the electric field reaches its breakdown point. At this time, discharges occur either from one cloud center to another or from the cloud-to-earth. Fig. 2-12 demonstrates the time sequence of these events that are the dynamics of the lightning phenomena. The formation of the stepped leader, the first return streamer, and then dart leaders and subsequent return strokes (which are repeated) are shown. The time values shown are approximate; there is considerable debate over the time duration and velocity of propagation of the stroke. More is said later concerning the stroke velocity in par. 2-3.5.

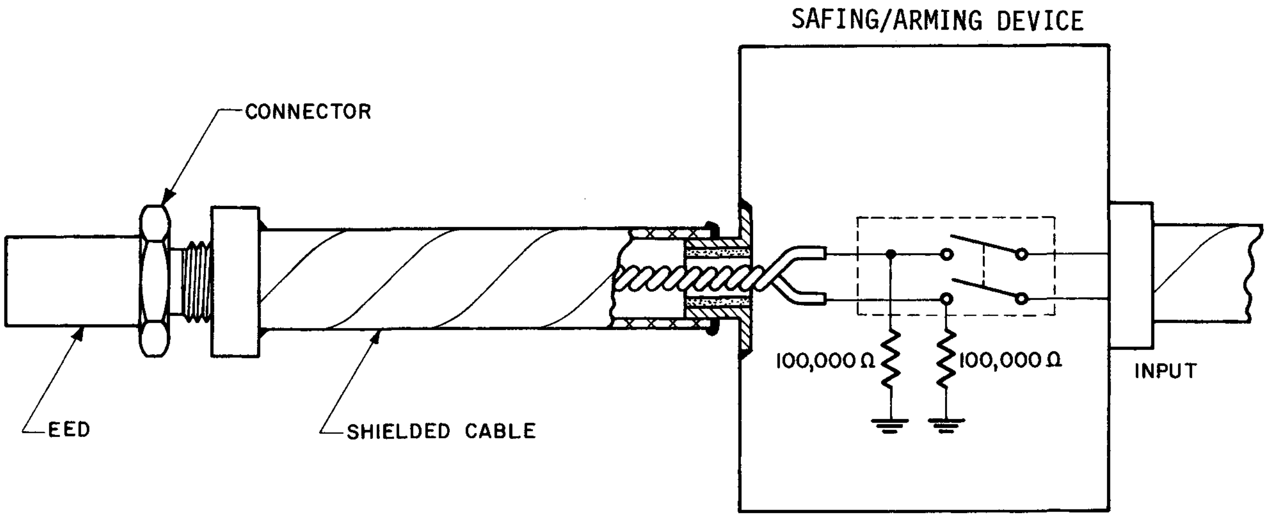
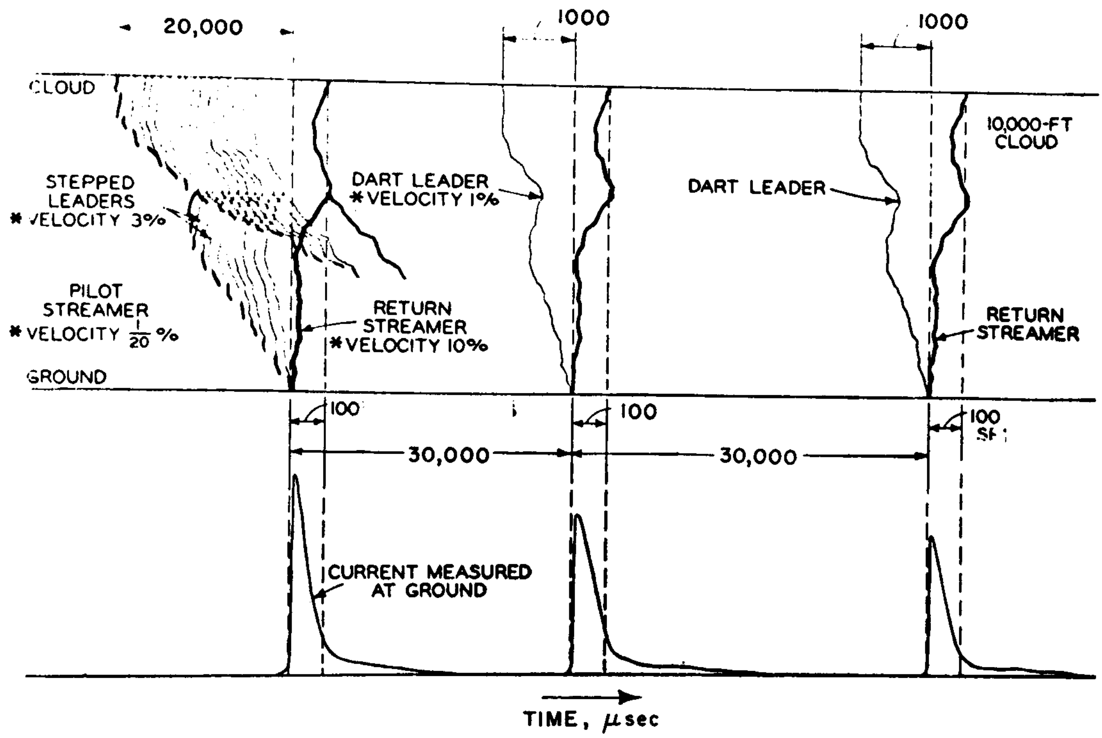


Fig. 2-11. Installation of Static Electricity Bleed Resistors



* IN REFERENCE TO THE VELOCITY OF LIGHT

Fig. 2-12. Sequential Phenomena in the Formulation of Lightning Discharge

In flight, practically the same hazards exist for missiles as those which occur at the launch site. Direct strikes and induced effects from both electric and magnetic fields exist as hazards. The main difference in the hazards in the two cases is that the exposure time for high-flying missiles and aircraft is reduced while flying through the storm area that usually extends from ground level to altitudes of 40,000 ft. Strikes of lightning recorded on jet aircraft show a reduced incidence of occurrence over propeller-driven aircraft. This difference is attributed to the much higher altitude at which jet aircraft operate. Another difference between missiles and aircraft in flight and those on the ground is that no in-flight ground gradients exist.

Experimental evaluation of the effects of lightning on aircraft has been undertaken with models and under full scale conditions with lightning-simulating surge generators and more recently with natural lightning (Ref. 20). Results have shown that abrupt changes in the electric field occur inside an aircraft for strokes that pass within 500 yd of the aircraft.

When in flight, most lightning hazard dangers are the result of cloud-to-earth discharges. Cloud-to-cloud discharges do not contain the return stroke component characteristic of cloud-to-earth discharges. The current maximum for cloud-to-cloud discharge is, therefore, approximately three orders of magnitude less than that of the cloud-to-earth discharge. Furthermore, the time rate of change of both the magnetic and electric fields is considerably less with the result that the induced effects are also reduced.

One question that must be answered is: How often do thunderstorms occur? The answer varies with geographical location and the time of the year. Isokeraunic maps have been developed that show the number of thunderstorm days per year that can be expected in certain areas (Ref. 21). Fig. 2-13 is a sample of such a map for the world. Notice that central Africa has an incidence of 80 thunderstorm days per year and that North Africa, in the arid regions, has an incidence of 5 or less. It is important to remember to consider how often a weapon system will be confronted with lightning storms. In installations that are located only in polar regions, for example, there would be little reason to provide lightning protection while, generally, tropical areas have a high thunderstorm incidence and protection is required. If a system is to be used in all climates, then protection should be considered for the most severe environment.

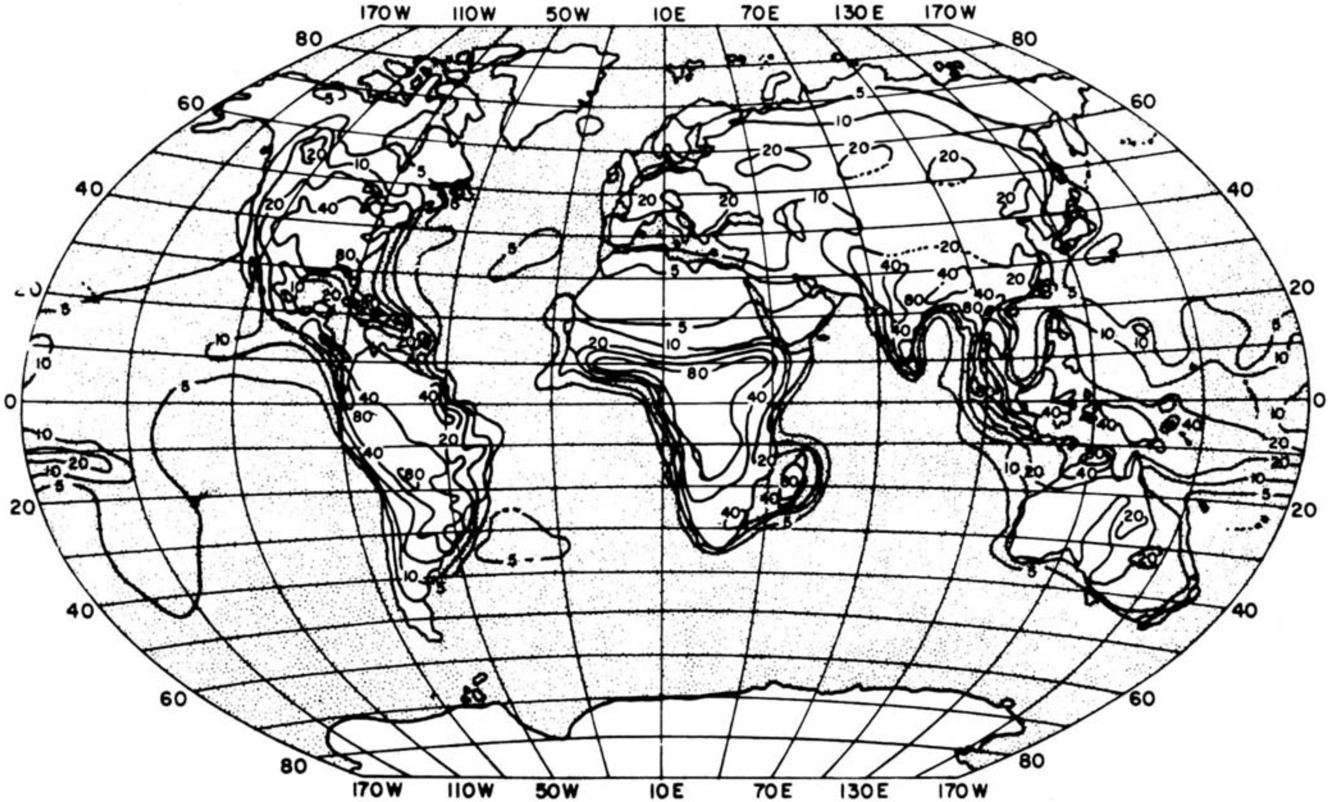


Fig. 2-13. Average Annual Number of Days With Thunderstorms (World)[21]

2-3.1 COMPONENTS OF A LIGHTNING DISCHARGE

The cloud-to-ground discharge begins with a pilot streamer that propagates earthward at about 0.15 m/μsec (Ref. 22). This is followed by a leader that is a series of short stepped strokes. Repeated starts are made but the cloud is unable to supply charge into the leader rapidly enough to sustain the discharge to earth or between clouds. Eventually the charge catches up with the current requirements and the stepped leader reaches the earth.

When the stepped leader reaches the earth, the negative charge on the cloud is effectively brought closer to the earth with the result that the potential gradient, or electric field, is increased. The currents involved in the stepped leader are normally less than 200 A and the velocity of the charge front is relatively small, being only about 10 m/μsec. At this time, the charge formerly on the cloud is suspended in a column from the cloud to the earth, and the head of the positively charged column then propagates from the earth upward toward the cloud to neutralize this negative cloud charge. This neutralizing process results in the main stroke that proceeds with a velocity of about 180 m/μsec and with currents on the order of from 1,000 to 200,000 A.

There is little radiation from the stepped leader compared to that from the main stroke; the reason is that the change of field from the main stroke is approximately three orders of magnitude less in time than that from the leader. The radiated field is proportional to the time rate of change of the electric field. The relative time of the leader and main strokes may be compared in Figs. 2-12 and 2-14. More is said concerning the discharge process in par. 2-3.5.

Repeats of these phenomena are common. The stepped leader is generally replaced by a "dart" leader that re-establishes the path from earth-to-cloud for all strokes other than the first in a series.

2-3.2 CURRENT AND CHARGE

The magnitude of current, initial charge, and charge height varies widely from discharge to discharge. This factor alone probably accounts for much confusion in the theoretical and experimental treatment of lightning data.

The current that is contained in the main stroke can cover a considerable range of values. While there is much information in the literature concerning the magnitude of this current, most of the experimental information that is available is attributed to Norinder (Refs. 23, 24). Through painstaking measurements taken over a long period of time, enough signatures of lightning discharges were obtained to permit some valuable statistical deductions. These data are summarized and compressed into the waveform shown in Fig. 2-15. This waveform can be considered representative of a typical lightning discharge; although the smooth representation of this stroke is not, of course, typical of those obtained in practice.

The following quantitative information concerning lightning strokes was summarized from data secured by several investigators through measurements of strikes to transmission towers and indicates orders of magnitude (Ref. 21).

(1) Median number of components (discharges) in a stroke	2
(2) Median time interval between components	0.02 sec
(3) Median crest current	16,000 A
(4) Maximum crest current	220,000 A
(5) Median rate of rise of current	10,000 A/μsec
(6) Median time for current to drop to half of its crest value	43 μsec
(7) Median total charge in stroke	30 C
(8) Maximum total charge in stroke	164 C

2-3.3 FREQUENCY SPECTRUM

A lightning discharge has associated with it radiation in the form of light and sound, and radiation in the form of electromagnetic, electrostatic, and induction fields. It is the electrical radiation in which the system designer is most interested. A generalized current waveform from which radiation results is plotted in Fig. 2-15. Both the main component of the discharge and the so-called "superimposed variations" (Refs. 23, 24) contribute to the total radiation spectrum characteristic of lightning discharge.

Norinder (Ref. 23) has observed variations that have a random occurrence; however, the changes that do occur appear to have frequency components that are much higher than those of the total waveform without the variations. This may account for high frequency radiation components that have been observed.

There is no standard lightning discharge spectrum. Differences have been observed in lightning spectra in various locatities of the world and even with simultaneous observation of the same discharge from different locations.

Average spectral data from a number of these observers are shown in the composite source spectra of

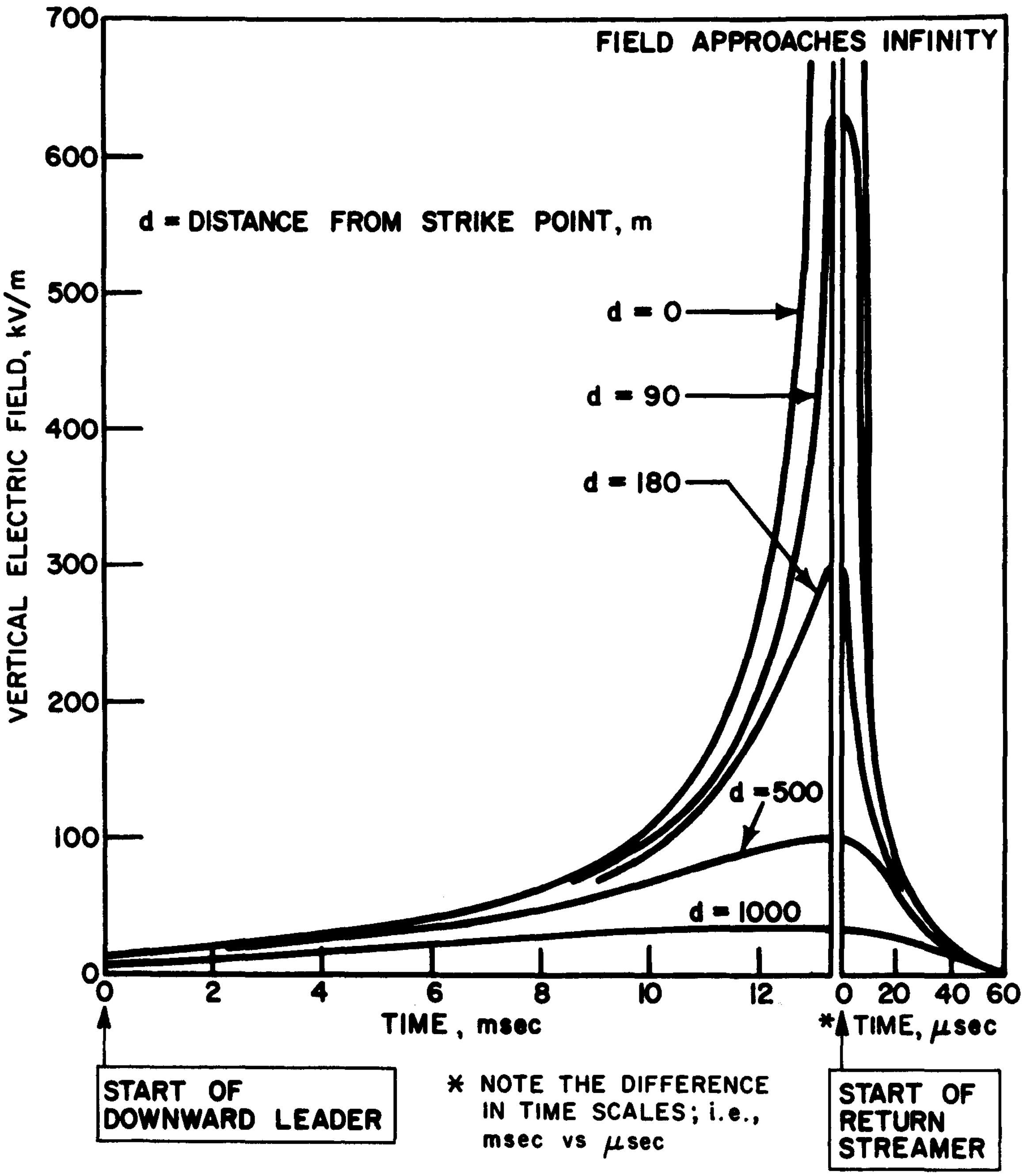


Fig. 2-14. Electric Field of a Lightning Stroke Resulting from the Leader and Main Stroke

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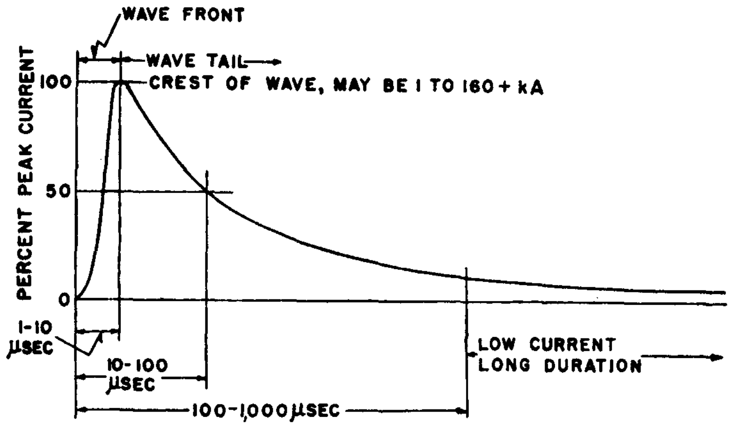


Fig. 2-15. Generalized Wave Shape of Lightning-stroke Current

Fig. 2-16 (Ref. 25). In this figure, the response at 7 kHz is taken as 100 and the response at other frequencies is normalized on this basis.

These average data, that have been compiled by Croom, represent the work of Norinder resulting from observations of current waveforms of close discharges, of Florman observing close discharges, of Croom observing distant discharges, of Taylor and Jean observing groundwaves from close discharges, from Bruce and Golde observing current surges in transmission lines, from Hepburn observing slow tails, and from Hill who made theoretical studies. The results are therefore an agglomerate of information.

2-3.4 STATIC ELECTRIC FIELDS

The magnitude of the fair-weather static electric field is on the order of 100 V/m at the surface of the earth and about 2 V/m at an altitude of 10,000 m. This picture changes considerably during the passage of thunder clouds. Estimates have been made of the gradient of the electric field at ground level just prior to a stroke from a charge center in a cloud (Ref. 22).

Conditions of the cloud centers are quite varied. Heights can vary from a minimum of less than 150 m to over 10,000 m. The average cloud height is 2,000 m. Charges that produce a single discharge vary from 1 to

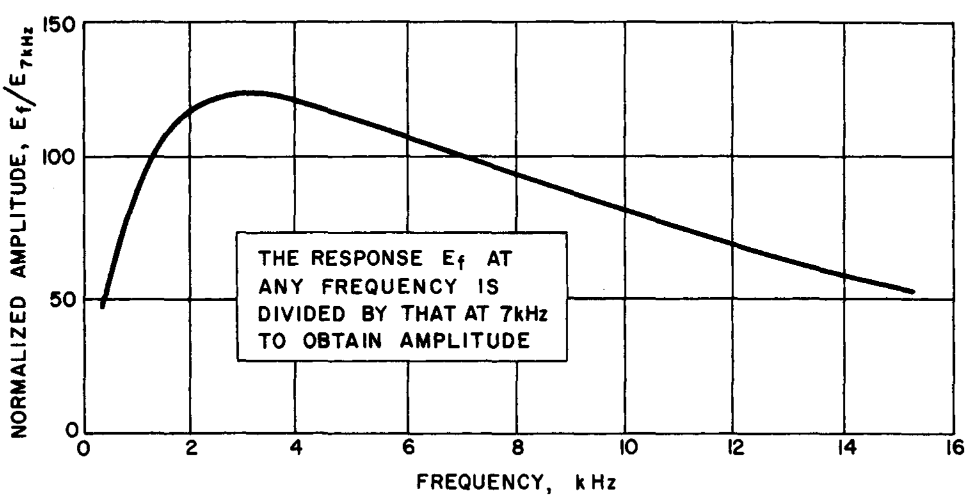


Fig. 2-16. Normalized Average Amplitudes from a Number of Observations as a Source Spectrum for Lightning Discharges

CHAPTER 3

CONCEPTS FOR HARDENING WEAPON SYSTEMS AGAINST RF ENERGY, LIGHTNING, AND STATIC ELECTRICITY

3-1 GENERAL

The weapon system designer can correctly apply the general concepts for hardening against Electromagnetic Radiation (EMR) only if he understands the basis of the concepts. A lack of such understanding leads to the blind application of approximations in circumstances where they are not valid. The use of approximations in weapon system EMR hardening is, however, unavoidable; therefore, the designer must be aware of the areas of uncertainty.

Information on RF susceptibility and static electricity sensitivity of certain common weapon system components (particularly in guidance, telemetry equipment, fuzes, and electroexplosive devices) has accumulated to a point where the designers can and should consider susceptibility data in selecting these components but, in general, little is known about the susceptibility of the bulk of typical weapon system components. As a result, RF protection is usually a "hardening" rather than a component selection task; most components are selected for characteristics other than their RF invulnerability.

RF hardening of a weapon system simply consists of decoupling the weapon components from the external electromagnetic environment. The electromagnetic environment criteria for the individual weapon system are described in the weapon system's Qualitative Materiel Requirements (QMR) and Technical Characteristics (TC).

In classical electromagnetic theory the two methods of reducing to zero the electromagnetic field components due to a single source, measured at some given point in space, are: (1) enclose either the receiving point or the radiating source inside a perfect electric or magnetic conductor, or (2) remove the source of radiation to an infinite distance. Both methods are used for protection against EMR; however, reducing the electromagnetic field to zero is not possible with practical methods. Generally, some level other than zero must be specified so that individual components of the weapon system can endure without impairing mission or safety objectives.

In general, the high frequency response of typical weapon system components under operating conditions is not well known. For example, the response of typical integrated circuit logic, high gain servo loops, individual transistors, diodes, etc., to high frequency stimuli applied in various ways to the components or subsystems is, in many cases, completely undefined. The amount of hardening or decoupling necessary to ensure that the weapon system will survive in the specified external electromagnetic environment is, therefore, not known. In practice the weapon system is hardened until the amount of coupling seems so low that the probability of malfunction is low.

The general problem of predicting the amount of hardening necessary can be illustrated by considering a weapon system immersed in a known multisource electrical environment. If the physical environment and the weapon system itself were completely specified, then we could predict the stimuli delivered to any component–due to the external environment–by solving an electromagnetic boundary problem.

The classical boundary value problem can be stated as follows: *Given the location, shape, size, and electrical parameters of every object in space, find the electric and magnetic fields everywhere in space for all times due to an electromagnetic source current that is completely described in terms of its spatial and time dependence.*

Patently, it is not that easy. Exact solution of such problems, even with relatively simple geometric shapes

for both boundaries and sources, is extremely difficult. Progress is being made by computer approximation to solutions (Ref. 1), but even here the boundaries are relatively simple geometrically. The *exact* solution of the boundary value problem involving the components of a modern weapon system and a typical external electromagnetic environment is decidedly beyond economic solution. Further, every change made in either the weapon system or the external electromagnetic environment would require a new solution; and each new solution would be on the same order of complexity as the previous one. This, plus the fact that the external electromagnetic environment will probably be an unknown due to differing sources and external bodies, indicates that there is no hope for an exact solution to the general problem, even in greatly simplified cases.

The electromagnetic current source mentioned in the statement of the general boundary value problem is, in essence, any source and in consequence assumes different aspects in different problems. For instance, in one problem the source may be a known electrical current at some place in space; in another problem it may be equated with a known electromagnetic field in some portion of space. In this latter case, the source can be treated equivalently by considering related electrical and magnetic surface currents over the volume in which the electromagnetic field is known. The magnetic surface currents cannot, it is presently believed, exist but are convenient to assume for analytical purposes. This concept of the source as a known electromagnetic field in space is the one usually used in hardening evaluation. The electromagnetic field in which the weapon system is required to survive is assumed to impinge upon the weapon system. This is equivalent to assuming that this required field is the only significant field that originates far away from the weapon system.

It has been found *experimentally* that the solutions to these problems–for objects that are large enough to be described by bulk or average electrical parameters (permittivity, permeability, and conductivity)–always satisfy the set of partial differential equations proposed by J. C. Maxwell; hence, the analytic approach to the general boundary value problem is to seek a solution that satisfies Maxwell's equations and the given conditions.

Historically, the solutions of electromagnetic problems were first obtained at frequencies such that the objects involved were much smaller than the wavelength of the source frequencies. These solutions satisfied what are today called Kirchhoff's Law and are the basis of modern circuit theory. Methods of analysis of electrically long uniform structures evolved from circuit theory and developed into modern transmission line theory. At this point it was recognized that the assumptions of the circuit and transmission line theories were specializations of, or approximations to, Maxwell's equations. The very large body of knowledge, experience, and methods that makes up circuit and transmission line theory is almost universally used in the solution of complex electromagnetic problems. The analyst usually reduces the complicated electromagnetic field problem to a point where circuit or transmission line theory can be applied. The analytic solution of all the technical problems in electrical engineering can be considered as solutions to a general boundary value problem.

Practical methods for solving boundary value problems lean heavily on several approximations. First in importance is the assumption that all matter involved in the problem is such that the electrical and magnetic parameters (permittivity, permeability, and conductivity) of the matter do not depend upon the magnitude or polarity of the electromagnetic fields in the matter. This approximation is often stated more stringently so that the electrical parameters of the matter are also independent of time. This is equivalent to saying that the parameters are constants at any one frequency. This approximation is usually an excellent one for the ranges of electromagnetic fields and materials normally encountered in weapon systems. Materials that are prime examples of elements that are not linear are magnetic materials, rectifying elements (such as semiconductor junctions or point contact diodes), and bolometer elements.

The linearity assumption is usually justified, in most practical problems, since the number of elements exhibiting nonlinear behavior is quite small in relation to the total number of elements in the overall weapon system; hence, the amount of energy "scattered" in a nonlinear element is small and will not seriously change the overall linear behavior of the fields except in regions quite close to the nonlinear elements. For example, when a missile is weakly irradiated by a remote transmitter, there is no reason to expect the electromagnetic fields existing in the volume between a missile's skin and its internal "black boxes" to exhibit any nonlinear behavior due to the presence of conventional electronic circuits containing transistors in the black boxes. In contrast, the effect of an extremely intense nearby magnetic field source on a weapon system containing large quantities of steel, which could be driven into saturation by the high magnetic fields, might very well be nonlinear.

If it is assumed that all materials involved in a weapon system are linear, then the solution of the problem will be a linear solution, making it possible merely

to add separate responses due to separate sources to obtain the system's total response to the several sources. The linearity of the problem also allows the use of the many sophisticated transient analysis techniques which would seem to be very valuable. However, the sources (and the conditions of the whole problem in general) are usually so ill defined that Fourier and Laplace transforms in relation to time cannot be used to much advantage.

Other approximations can be used for particular types of matter. Metals are usually assumed to be perfect electrical conductors in their effect on external fields. Air and common dielectrics are assumed to be completely lossless.

Even with these assumptions the complex geometry of a typical weapon system and its environment preclude a simple solution to the practical problem of predicting the amount of RF energy a given system component will pick up. Solutions can be adapted from much simpler geometries, however. The most commonly used method is to separate the overall problem into several simplified sections. As an example, this approach would divide the complex problem of a weapon system hardening prediction into the several sections shown in Fig. 3-1(A), (B), and (C). The portion shown in Fig. 3-1(C) is actually an approximation to the more complicated problem shown in Fig. 3-1(D). The validity of a division approach, of course, depends upon the degree to which the sections resemble the actual problem. Often the individual section can be treated by some "worst case" method which yields valuable RF protection information irrespective of the variables that relate one portion of the overall problem to another. Results of this type are among the most definitive obtainable in complicated electromagnetic problems. Varying the physical componentsthat represent the weapon system in each of these individual problems, such that overall field levels are reduced, corresponds to a method of protection of the missile system components.

The example shown in Fig. 3-1 reflects one method of specifying the overall problem and also indirectly illustrates methods used to protect weapon systems.

Fig. 3-1(A) illustrates the simplest operational method of protecting a weapon system, i.e., maintaining large distances between potential sources of RF energy and the weapon system. Fig. 3-1(B) illustrates the concept of shielding by the interposition of a metallic structure between the incident field and the volume of space in which a reduced field is desired. The model antenna (Fig. 3-1(C)), if the component to be protected and its associated circuitry are properly designed, can form a very poor receiving antenna. Another method is to insert an RF suppression device in cascade with the component to be protected, which will lower any expected stimulus to a tolerable level. A general discussion of these three methods follows; a specific discussion of each and their application to weapon system protection is given in Chapter 4, Design Techniques.

3-2 SEPARATION

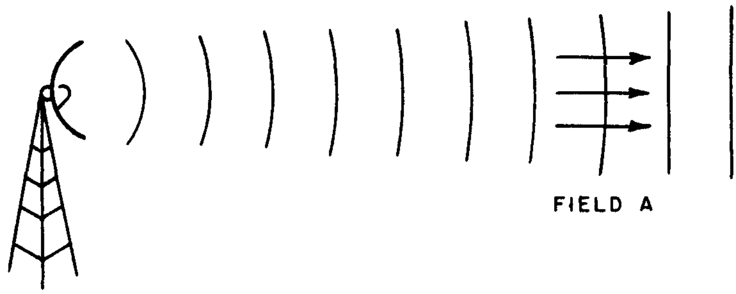
In free space, at distances large in relation to both the physical dimensions of the source and the wavelength of the source frequency, the magnitudes of both the electric and magnetic fields vary inversely with distance, and the power density of the entire electromagnetic field varies inversely with the square of the distance. In actual practice these variations are complicated by the effects of the material environment. At large distances, departure from the free space variation can be looked upon as due to either reflections or a guiding property of the environment. Guiding is usually considered as a variation due to the shape of the terrain or the presence of a reflecting layer in the ionosphere. At the higher frequencies, such as those used by search radars, departures from inverse square power variation can almost always be attributed to reflections. Departures at the communication frequencies, in contrast, are usually considered as due to guiding properties of the environment.

In actual practice, the designer does not have any control over the separation between the system and the source of EMR; therefore, he must base his calculations on the electromagnetic field in which his weapon system is required to survive. The required survivable field is usually classified information and can be determined by the designer by examination of the weapon system's Qualitative Materiel Requirements and Technical Characteristics.

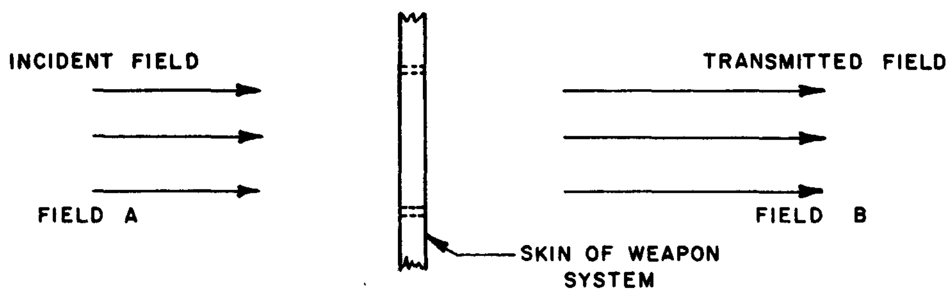
There is a great amount of similarity between the overall hardening problem (EMC), and the RFI/EMI and personnel hazard problems. The RFI/EMI specifications (see Fig. 3-2) (Ref. 2) require measurements in electromagnetic fields of no more than 10 V/m. A personnel hazard level of 195 V/m (Ref. 3) (100 W/m^2) has been accepted by the military and, for many manned weapon systems, is often appropriate as a design goal for hardening.

3-3 SHIELDING

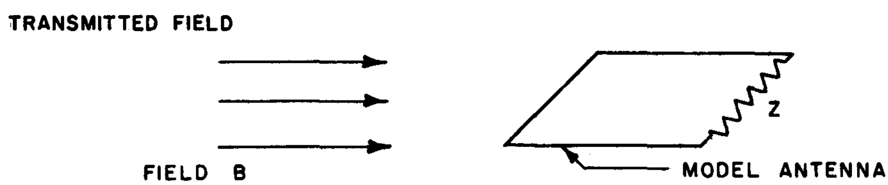
Shielding as a concept for protection of weapon systems usually refers to the interposition of a metallic



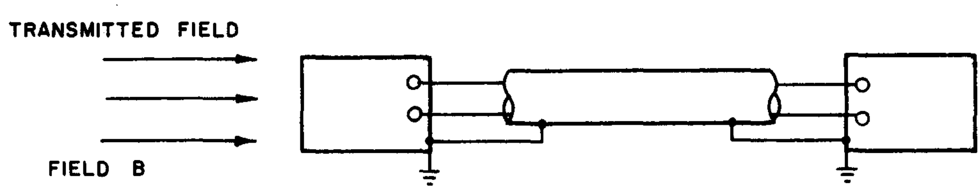
(A) REDUCTION OF THE FIELD BY SEPARATION



(B) REDUCTION OF THE FIELD BY SHIELDING



(C) FIELD IMPINGES ON EQUIVALENT CIRCUIT IN WEAPON SYSTEM



(D) FIELD IMPINGING ON ACTUAL WEAPON SYSTEM COMPONENTS

Fig. 3-1. A Common Division of the Overall Problem

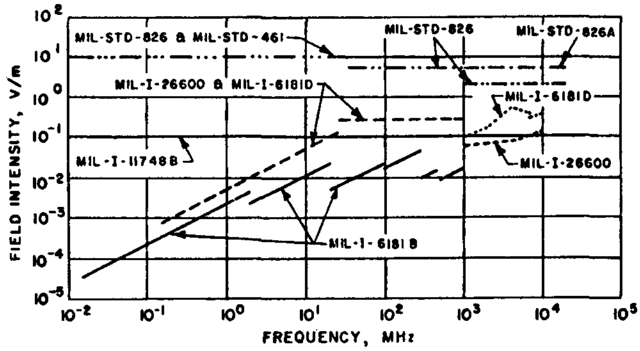


Fig. 3-2. RF Radiated Susceptibility Limits[2]
Reprinted from Electronic Engineer, Chilton Co., July 1968, by permission.

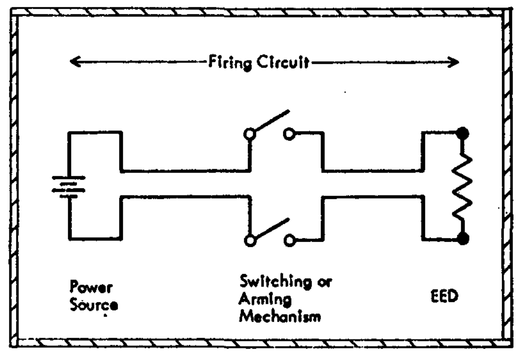
structure between the source of the electromagnetic energy and the items to be protected. For solid metal shields that completely enclose the items to be protected, the protection provided by the shield can be conveniently broken down into a loss due to energy reflected and a loss due to energy absorption.

The division of the total loss into these components becomes rather indistinct for shields that are not solid or do not completely enclose the items to be protected; however, reflection losses can loosely be considered as that energy radiated back toward the source by currents induced in the shielding material. High reflection loss, therefore, requires materials in which currents can easily be induced. Solid metals of high conductivity are ideal for this application but other common shielding materials are often used as compromises–such as metal screens, meshes, and braids. Also, considerable shielding can be obtained purely by the construction of support members and by "black box" housings.

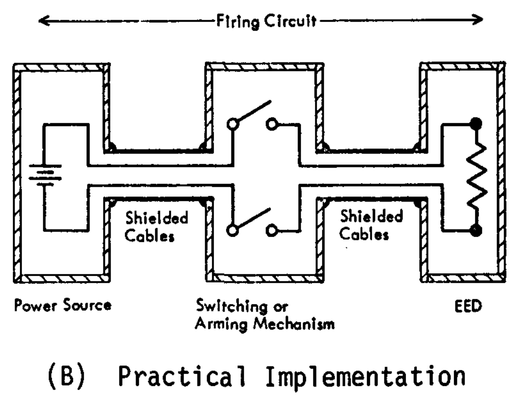
The preferred method of shielding encloses the entire system to be protected inside a seamless metal shield. Fig. 3-3 shows a sketch of the development of such a system. The practical problems of shielding development are mainly concerned with the joints, seams, and connectors necessary in practical implementation of the complete enclosure of the system to be protected.

3-4 ELECTRICAL CIRCUIT CHARACTERISTICS

The electrical and physical characteristics of the electrical circuits which are associated with the items to be protected influence both the amount of energy received by the circuit and its distribution among the various items to be protected. The designer's task is to make the circuit a very inefficient antenna.



(A) Primitive Shielding Concept



(B) Practical Implementation

Fig. 3-3. The Conductive Box Concept

Circuits that are composed of unshielded wires can often be treated as linear antennas, and upper limits can be set on the amount of energy that they can extract from a given incident field over large portions of the

frequency spectrum. Design concepts can be developed from this treatment such that the maximum energy extracted from the field is minimized. Often techniques of this type result in various electrical and mechanical design guides such as balanced circuits, twisted pair wiring, etc. These protection techniques are dictated by analysis that usually cover only part of the frequency band that may be of concern for weapon system protection; hence, if a wide frequency band is of concern, there can be some confusion as to which techniques should be used.

3-5 DIRECT PROTECTION OF COMPONENTS

Once a system has been designed, modification is usually expensive. In this case, or occasionally as a trade-off in original design, and in cases where it is not possible or feasible to evaluate the effectiveness of other protection techniques, components can be protected by adding special protection devices to the system. These must function over the entire frequency range to which the item it protects will be exposed. Further, it should not interfere with the normal operation of the circuit. The magnitude of protection afforded is difficult to ascertain since the equivalent generator and load impedances at the point at which the protective device is to be inserted almost never are known as a function of frequency. In addition, the device must usually provide protection in both balanced and unbalanced modes of excitation.

As a result of these many unknowns and complexities, several parameters which purportedly describe the protection provided by the protective device cannot be relied upon under actual operating conditions. There are, however, ways of specifying the attenuation of the protective device such that it will, in all situations, have the minimum attenuation specified. A thorough examination of the protective parameters that are quoted for a protective device is recommended before procurement. This is discussed in detail in par. 4-4.

In general, the direct protection of components includes the selection of nonsensitive components. In the case of new design that must utilize highly sensitive components, direct protection using cascaded protective devices should always be considered.

REFERENCES

1. C. L. Frederick et al., *Digital Computer Program for Determining the Effect of High-Level RF Exposure on Missile Systems,* Report No. RE-TR-66-10, Vitro Laboratories, Silver Spring, Maryland, May 1966.
2. C. B. Pearlston, "What is Wrong With EMI Specifications", The Electronic Engineer **27**, 66 (1968).
3. MIL-I-6181D, *Interference Control Requirements, Aircraft Equipment,* 25 November 1959, p, 14.

CHAPTER 4

DESIGN TECHNIQUES

This chapter covers the principal protection concepts and their applications to practical design problems. The overall protection concepts treated are:

1. Shielding
2. Electrical circuit characteristics
3. Direct protection of components

4-1 SHIELDING

4-1.1 SHIELDING EFFECTIVENESS

An ideal shield completely surrounds the volume it protects with a solid metal covering having no openings, joints, or other discontinuities. In general, such a structure is negated by other design requirements. The joints and openings in the metal of the shield are, in almost all cases, the main source of electromagnetic leakage into the shielded volume. The effectiveness of a closed solid metal shield in excluding electromagnetic energy from the interior items depends upon:

1. Conductivity G_R of the metal shield in relation to copper
2. Permeability μ_R of the metal shield in relation to free space
3. Thickness of the shield
4. Geometry of the shield
5. Contents and their position inside the shield
6. Wave impedance of the electromagnetic radiation incident on the shield at every point of the shield
7. Frequency of the incident radiation

The effectiveness of shields that have joints, breaks, holes, penetrations, perforations, or other types of discontinuities depends–in addition to the parameters previously cited–very heavily on the type and dimensions of the discontinuity.

Much effort has been expended in the past to determine by analysis the effectiveness of solid metal shields. Appendix A of this handbook covers some of this work in detail, and gives graphs and nomographs of the results obtained by these techniques. These methods, however, are based on the assumption that the interior of the shielded volume is infinite in extent so that energy entering the volume is never reflected or perturbed. This assumption is of paramount importance in the formulation of the classical shielding effectiveness analyses. It rests on a power ratio to be written as the square of the magnitude of the ratio of two electric or two magnetic field strengths since it allows both field strengths to be theoretically associated with waves of precisely the same impedance. The conservation of power must be the basis of any evaluation of shielding effectiveness and, since the classical methods of evaluating shielding effectiveness provide only field strength information, the assumption of no reflections inside the shielded volume (which is equivalent to assuming that the impedance of the measurement point does not change if it is enclosed in a complete metal shield) is critical to the validity of the shielding effectiveness predicted by these classical methods.

The closed metal shields used in weapon system design, ignoring the very complex equipment usually enclosed by these shields, quite clearly modify the impedance conditions assumed in the classical evaluation. If the assumptions of the classical shielding effectiveness evaluation were satisfied, the shielding effectiveness ratio so derived would relate, in dB, the power density incident on the shield to the power density immediately inside the shield. For weapon system shields, and almost all other practical applications of shielding for that matter, the classical shielding effectiveness does not correctly relate the power densities. Furthermore, the results so obtained may be greater than, equal to, or less than the actual values. In general, the results

normally predict a power density inside the shielded volume which is much lower than the actual value.

Since the actual shielding effectiveness of a shield depends heavily upon the geometry of the shield and, more important perhaps, on what the shield contains and its position, it would seem important to determine this dependence. However, this problem is equivalent to determining the impedance looking into the shielding volume (from the inner surface of the shield) at every point on the shield. Considering that the shielded volume will be full of complex metal structures which affect theoretical propagation modes and cavity resonances, this effort is decidedly beyond economic solution either analytically or experimentally.

It is recommended that the shielding designer read Appendix A if he desires to become more familiar with the basic approaches, definitions, and techniques of shielding analysis. He can, however, utilize the information given in this chapter to evaluate the performance of weapon system shields.

Although the impedance looking into the shielded volume is unknown, the effectiveness of the shield can be evaluated in a conservative manner for most practical shielding problems by assuming that the region internal to the shielded volume always presents an impedance equal to the complex conjugate of the shield impedance to every point in the inner surface of the shield. This procedure results in a shielding effectiveness parameter C defined as

$$C = T_p + A - 3 \tag{4-1}$$

where

C = ratio of the power density incident on the shield to the maximum power density that can exist, irrespective of the contents or its geometry, immediately inside the shielded volume, dB

T_p = power transmission loss of the power density incident on the shield to the power density in the shield, dB

A = absorption loss; i.e., actual dissipation of energy as heat of the shield and is identical to that from the classical shielding effectiveness calculations, dB

The parameter C is directly applicable only to solid, closed metal shields but has indirect application to perforated or leaky shields. This conservative loss parameter can be counted on to predict a conservative estimate of protection provided by the shield if the absorption factor A is 10 dB or greater.

Another limitation of the parameter C, or for that matter any shielding parameter, is its dependence on the value of relative permeability μ_R. The values of relative permeability for magnetic materials is, in general, not well known above 150 kHz, and the shielding designer is thus without pertinent information for a large part of the frequency range to be considered. A conservative approach is to use published values of permeability and assume that μ_R has the value of one when there is no published value.

Another problem involved with permeability evaluation is that of saturation. The values of the relative permeability of magnetic materials is a function of the magnetic field strength in the material. Normally, only the small signal value of μ_R is quoted in the literature.

If the shield is to be exposed to very high magnetic fields, the incremental value μ_R will instantaneously vary from the small signal value to some much lower value. This results in harmonic generation in the field and, so it is thought, in a lower shielding effectiveness. Very little is presently known about large signal shielding effectiveness of magnetic materials.

4-1.1.1 Loss Mechanisms

The ratio of the power density incident on a shield, that is terminated in the complex conjugate of its own intrinsic impedance, to the power density into the matching impedance can be written as†

$$\frac{PD_i}{PD_s} = \left(1 - \left|\frac{Z_s - Z_w^*}{Z_s - Z_w}\right|^2\right)^{-1} \frac{e^{2\alpha x}}{2} \tag{4-2}$$

where

PD_i = incident power density, W/m^2

PD_s = maximum power density into the shielded volume, W/m^2

α = attenuation constant of the shield, mil^{-1}

x = thickness of the shield, mil

Z_s = intrinsic impedance of the shield, Ω

Z_w = incident wave impedance, Ω

Z_w^* = complex conjugate of Z_w, Ω

The vertical lines in the equation denote magnitude of the enclosed complex quantity.

Eq. 4-2 assumes that the absorption loss of the shield is high enough so that the input impedance to the shield

†A list of symbols with a brief definition is presented at the beginning of handbook.

is the intrinsic impedance of the shield and not an impedance dependent on the conjugate impedance terminating the shield.

The exponential term of Eq. 4-2 is a function of the above shield parameters and can be associated with the power absorption, by heat, of the shield. The remaining term in Eq. 4-2 is a function of the incident wave impedance and the shield's intrinsic impedance. This term can be associated with the transmission or reflection of power at the incident wave/shield interface. We will call this the transmission loss and will associate T_p a dB ratio, with this loss. The factor of 2 in Eq. 4-2 is the result of assuming a complex conjugate rather than an intrinsic impedance termination for the shield.

Parameter C as given in Eq. 4-1 can also be written as ten times the logarithm to the base ten of Eq. 4-2. Thus

$$C = A + T_p - 3 = 10 \log \left[\frac{e^{2\alpha x}}{2} \left(1 - \left| \frac{Z_s - Z_w^*}{Z_s + Z_w} \right|^2 \right)^{-1} \right] \quad (4\text{-}3)$$

therefore,

$$A = 10 \log e^{2\alpha w} - 10 \log 2 = -3 \quad (4\text{-}4)$$

and

$$T_p = 10 \log \left(1 - \left| \frac{Z_s - Z_w^*}{Z_s + Z_w} \right|^2 \right)^{-1} \quad (4\text{-}5)$$

Eq. 4-5 can be simplified to

$$T_p = 10 \log \left(\frac{|Z_s + Z_w^*|}{4 Re\{Z_s\} \; Re\{Z_w\}} \right) \quad (4\text{-}6)$$

where

$Re\{Z_s\}$ is read "the real part of Z_s."

The parameter C is a function of the shield's thickness, conductivity, and permeability, as well as of the frequency and incident wave impedance. Parameter C is directly applicable only to closed metal shields. It will predict a conservative estimate of protection provided by the shield if the absorption loss A is 10 dB or greater. The conditions for A to be 10 dB or more reduce to

$$f_{MHz} \; G_R \; x^2 \; \mu_R > 8.95$$

where

x = shield thickness, mil
f_{MHz} = frequency, MHz
G_R = relative conducitivity, mhos
μ_R = permeability of metal shield in relation to free space

For example, a 20-mil copper shield would have 10 dB of absorption loss for all frequencies greater than 22.2 kHz and the parameter C would thus be applicable above this frequency.

It is recommended that the shielding designer provide at least 10 dB absorption loss over the frequency range of interest. Analysis of cases where the 10 dB criterion is not met are possible but are beyond the scope of this handbook.

4-1.1.1.1 Transmission Loss

The shield/source transmission loss T_p is defined as the ratio in dB of the power density incident on the interface to the power density at the interface, assuming that the input impedance of the shield is the same as the shield's characteristic impedance. The calculation of this loss is based on the assumption that the shield has 10 dB or more absorption loss A.

T_p, as shown in Eq. 4-5, can be written as

$$T_p = 10 \log \left(1 - |\rho_p|^2 \right)^{-1} \quad (4\text{-}7)$$

where

$$\rho_p = \frac{Z_s - Z_w^*}{Z_s + Z_w} \quad (4\text{-}8)$$

is the power reflection coefficient.

The quantity ρ_p as defined is similar to the normal definition of reflection coefficient as defined in transmission line theory. The exception is the complex conjugate term Z_w^* which in normal transmission line theory would not be conjugated. The conjugation of this term, however, allows for the consideration of complex incident wave impedances.

Computation of T_p can be simplified by rewriting Eq. 4-8 in the form shown in Eq. 4-6.

$$T_p = 10 \log \left\{ \frac{|Z_s + Z_w|^2}{4 \mathrm{Re}\{Z_s\} \; Re\{Z_w\}} \right\} \quad (4\text{-}9)$$

The characteristic impedance of a solid metal shield is (from Appendix A)

$$Z_s = (1 + j) \sqrt{\frac{\mu_R \; f_{MHz}}{G_R}} \times 2.61 \times 10^{-4} \quad (4\text{-}10)$$

The wave impedances considered important by the classical evaluation techniques are:

1. $Z_o = 377\ \Omega$, the free space wave impedance

2. Z_ℓ the radial wave impedance of a small loop antenna when the loop dimensions are much smaller than either the wavelength being radiated or the distance to the point where the impedance is evaluated

3. Z_d, the radial wave impedance of a small dipole when the dipoles' dimensions satisfy the same conditions as those given for the small loop.

At a distance of 1 ft and for frequencies below 100 MHz the expressions for these impedances can be written as

$$Z_\ell \cong 0.62 \times 10^{-6} f_{MHz}^4 + j2.4 f_{MHz} \tag{4-11}$$

$$Z_d \cong 0.0153 f_{MHz}^2 - j\left(\frac{0.059 \times 10^6}{f_{MHz}}\right) \tag{4-12}$$

Table 4-1 gives T_p for the above three wave impedances and Table 4-2 compares the transmission loss of any shield for frequencies up to 100 MHz.

A study of Table 4-2 shows that T_p for the free space wave impedance is always less than the highly reactive wave impedances of the small dipole and small loop when the latter two wave impedances are evaluated 1 ft from the source and the frequency is below 100 MHz. A more detailed study of the values of T_p for higher frequencies and other distances from the dipole and loop sources shows that, for practical weapon system protection, use of T_p evaluated with a free space incident wave impedance gives a conservative loss estimate.

Fig. 4-1 plots the calculated values of T_p for a 377 Ω wave impedance as a function of frequency. Note that the ordinate is $T_p + 10 \log\sqrt{\mu_R / G_R}$. To use the figure for a shield characterized by a given value of μ_R and G_R, calculate

$$\zeta = 10 \log\sqrt{\frac{\mu_R}{G_R}} = 5 \log \frac{\mu_R}{G_R} \tag{4-13}$$

Now, at the frequency of interest, find where the frequency intersects the curve and read the ordinate value. Then subtract ζ from the ordinate value of Fig. 4-1.

TABLE 4-1

T_p FORMULAS

Wave Impedance, ohms	T_p, dB
Free Space $Z_o = 377$	$55.58 - 10 \log\sqrt{\frac{\mu_R f_{MHz}}{G_R}}$
Small Dipole at 12 in $f_{MHz} < 100$	$143.38 - 10 \log\sqrt{\frac{\mu_R f_{MHz}}{G_R}} - 10 \log f_{MHz}^4$
Small Loop at 12 in $f_{MHz} < 100$	$99.5 - 10 \log\sqrt{\frac{\mu_R f_{MHz}}{G_R}} - 10 \log f_{MHz}^2$

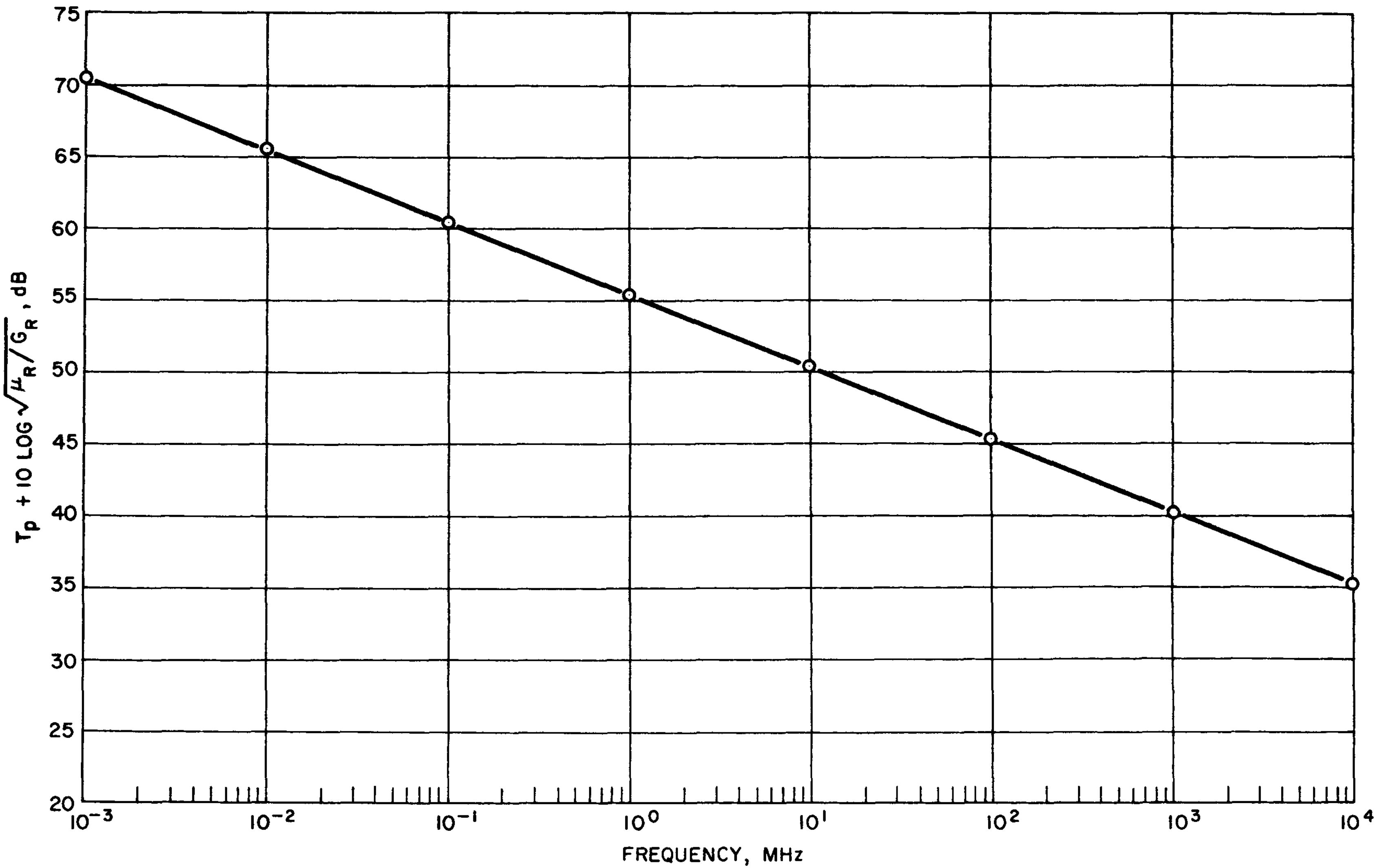


Fig. 4-1. Transmission Loss T_p for a Solid Metal Shield Irradiated by a Wave of 377-ohm Impedance

TABLE 4-2

COMPARISON OF TRANSMISSION LOSS FOR ANY SHIELD FOR THE COMMON WAVE IMPEDANCES

f_{MHz}	$T_p + 5 \log \left[\frac{\mu_R}{G_R}\right]$ in dB		
	Z_w = 377 ohms	$Z_w = Z_d$	$Z_w = Z_\ell$
100	45.48	49.5	53.38
10	50.58	74.5	98.38
1	55.58	99.5	143.38
0.1	60.58	124.5	188.38
0.01	65.58	149.5	233.38
0.001	70.58	174.5	274.38

The result is T_p for the given shield when a free space incident wave impedance has been assumed.

Values of G_R and μ_R for various metals are given in Table 4-3. The μ_R values are quoted at 150 kHz.

4-1.1.1.2 Absorption Loss

The absorption loss A in dB is the ratio of power density into a solid shield to the power density out of the complex conjugate impedance matched shield at the shield's interior surface; thus

$$A = 10 \log e^{2\alpha x} = 3.34 x \sqrt{G_R \, \mu_R \, f_{MHz}} \quad \text{(4-14)}$$

where x is the shield thickness in mils.

Fig. 4-2 plots A for a 1-mil copper shield (i.e., $\mu_R = 1$, $G_R = 1$) as a function of frequency. Any other shield thickness can be evaluated by multiplying the ordinate of Fig. 4-2 by $x_1 \sqrt{\mu_{R_1} \, G_{R_1}}$, where the subscript 1 refers to the material of the shield in question. Thus for a 20-mil aluminum shield

$$x_{aluminum} = x_1 = 20$$

$$G_{R_{aluminum}} = G_{R_1} = 0.61$$

$$\mu_{R_{aluminum}} = \mu_{R_1} = 1$$

$$\therefore \; x_1 \sqrt{\mu_{R_1} \, G_{R_1}} = 15.6$$

The ordinate values of Fig. 4-2 would be multiplied by 15.6 to obtain the absorption loss for the 20-mil aluminum shield.

The absorption loss A can also be found easily from the nomograph given in Fig. 4-3. A straightedge should be positioned between the $\mu_R G_R$ product of the shield of interest on the lefthand scale and the frequency of concern on the righthand scale. The intersection of the straightedge and the center scale then gives A, the absorption loss in dB/mil directly.

In general, the solid shields used in weapon system protection will provide absorption losses greater than 10 dB until quite low frequencies are approached. That is, an absorption loss of 10 dB is assured if

$$f_{MHz} \, x^2 \, G_R \, \mu_R \geq 8.95 \quad \text{(4-15)}$$

Table 4-3, in addition to listing the μ_R and G_R values of various metals at 150 kHz, also gives absorption loss A at this frequency in dB/mil. The G_R values are, as far as presently known, applicable for all frequencies below those of visible light.

4-1.1.1.3 Total Loss

The conservative loss parameter as given in Eq. 4-1

$$C = T_p + A - 3$$

TABLE 4-3

ABSORPTION LOSS OF METALS AT 150 kHz

Metal	Relative Conductivity, G_R	Relative Permeability, μ_R	Absorption Loss, dB/mil
Silver	1.05	1	1.32
Copper, annealed	1.00	1	1.29
Copper, hard drawn	0.97	1	1.26
Gold	0.70	1	1.08
Aluminum	0.61	1	1.01
Magnesium	0.38	1	0.79
Zinc	0.29	1	0.70
Brass	0.26	1	0.66
Cadmium	0.23	1	0.62
Nickel	0.20	1	0.58
Phosphor-bronze	0.18	1	0.55
Iron	0.17	1,000	16.9
Tin	0.15	1	0.50
Steel, SAE 1045	0.10	1,000	12.9
Beryllium	0.10	1	0.41
Lead	0.08	1	0.36
Hypernick	0.06	80,000	88.5*
Monel	0.04	1	0.26
Mu-Metal	0.03	80,000	63.2*
Permalloy	0.03	80,000	63.2*
Steel, 18-8 Stainless	0.02	1,000	5.7

*Obtainable only if the incident field does not saturate the metal

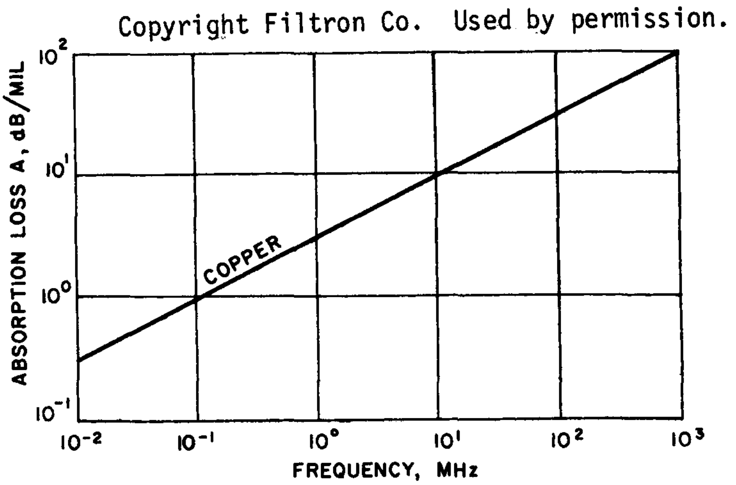


Fig. 4-2. Absorption Loss for Copper vs Frequency

T_p and A are calculated as described in the previous paragraphs. The parameter C can be used in two ways to facilitate the evaluation of weapon systems protection. First, it can compare the effectiveness of arbitrary solid shields against each other; second, it can evaluate the effectiveness of a particular shield in a particular weapon system/electromagnetic environment.

The first usage is straightforward. Plot C for the given environment for both shields and compare the results. The object of the second usage is to actually predict a margin of safety for the components inside the solid shield. The parameter C relates maximum power density immediately inside the shield to the incident power density. If the designer determines C for the chosen shield in the electrical environment the system is required to safely endure, then the total power W that can be transferred to the shielded volume can be easily calculated by multiplying the incident power density W/m^2 times the surface area of the shield m^2 and reducing the product by the amount of dB calculated for the parameter C.

For example, assume that it is desired to evaluate the protection provided by a 20-mil solid copper shield installed on all six sides of a 1-m cube. The electromagnetic environment is specified as 100 W/m^2 and the frequency range of interest is 1 MHz to 10,000 MHz. Further, assume that 1 mW of power at any frequency in the range of interest will not affect any of the components inside the shielded box. Parameter A can be found directly from Fig. 4-2 by multiplying the ordinate by 20. T_p is given directly by Fig. 4-1. By use of Eq. 4-1, C can now be computed for the 20-mil shield. The minimum attenuation occurs in 1 MHz (in this example) where C is approximately 119 dB. The total power that can be coupled through a cube having 1 m^2 faces is, therefore, 100 W reduced by 119 dB. If it is assumed that the field could impinge equally on all sides of the shielded cube, which is unlikely, a total power inside the cube of 600 W reduced by 119 dB is obtained. This is approximately 756×10^{-12} W, which is so far below the safe level of 1 mW that there is no reason to worry about the safety of the shielded components. The conclusions from this example should not lull the designer into thinking all shields are as effective. In general, all solid shields are very effective, but very seldom are complete solid shields used in weapon system protection.

For Z_w equal to 377 Ω, the computed total loss has a property that is quite useful in rough calculations: the parameter C, the total loss of any given shield, increases with an increase of frequency whenever the absorption loss A is 10 dB or more.

The evaluation technique described contains the following worst case assumptions:

1. The incident wave impinges equally on all sides of the shield (this is improbable).

2. The impedance just inside the shield (looking into the enclosure) is equal to the shield impedance (very unlikely).

The shielding values as predicted by this method are, without question, conservative.

4-1.1.2 Compromises in Shielding

The previous paragraphs have developed means of computing a conservative shielding effectiveness parameter for solid shields and also for evaluating the maximum amount of power that can be coupled into the completely shielded volume.

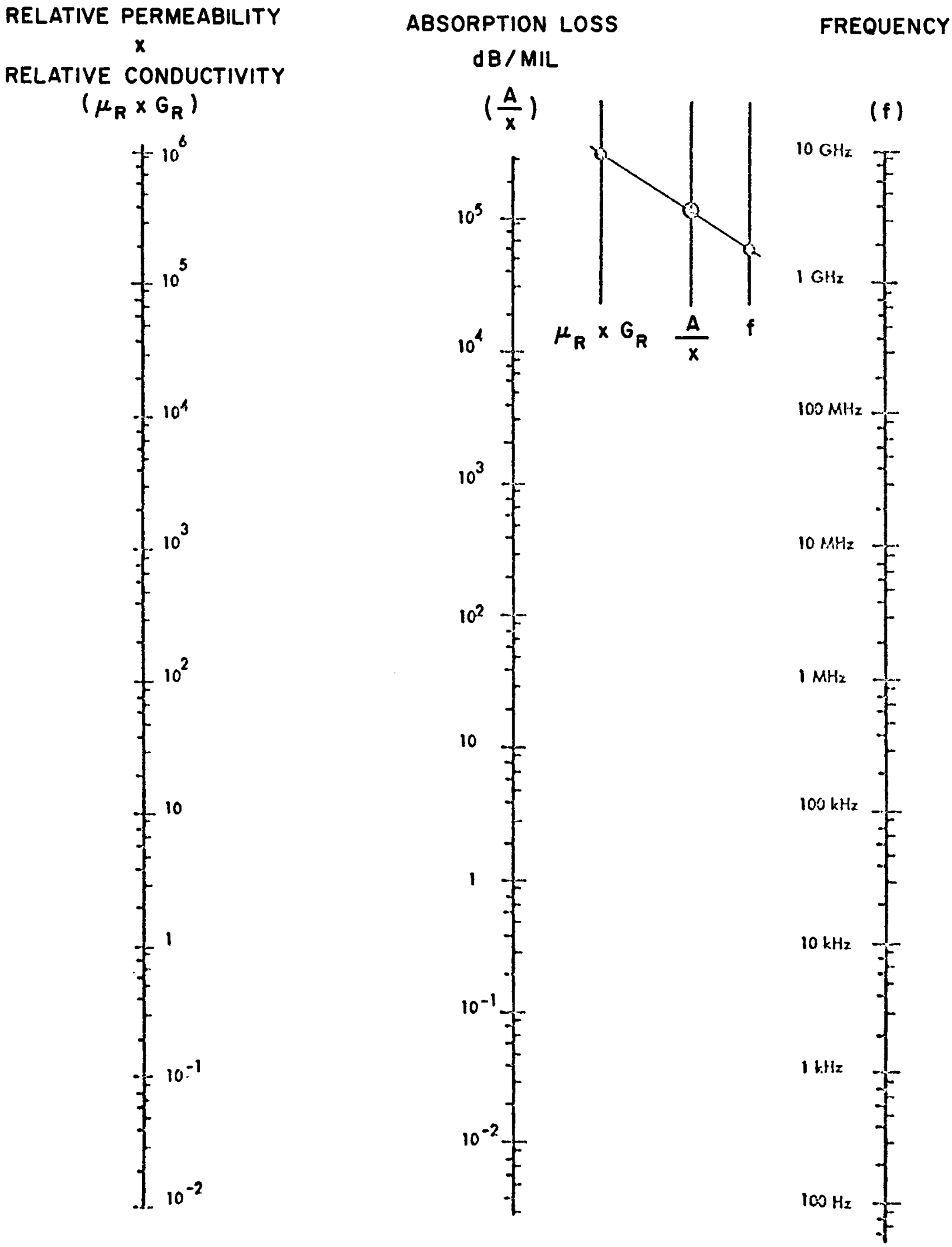


Fig. 4-3. Absorption Loss *A* of Solid Magnetic and Nonmagnetic Materials

A study of these paragraphs, particularly par. 4-1.1.1.3 will show that solid metal shields are extremely effective in reducing the overall level of electromagnetic energy that can be delivered to a component. The metal case of a typical weapon system must, however, have openings and other discontinuities for at least some of the following purposes: to pass power, control and output leads; to allow access for maintenance and servicing; to permit ventilation and environmental sensing; etc. The metal braided shield that often is used as a cover for the cables in a weapon system is itself a collection of small holes to which the previously discussed solid shielding effectiveness calculations do not apply. The evaluation of the leakage through holes, joints, seams, etc., in solid shields is considerably more difficult than evaluation of the protection provided by the solid shield. In general it may be stated that the discontinuities in the solid metal shielding surface are much more important in the evaluation of the leakage than the solid shield itself provided the shield is of reasonable thickness.

The designer's main concern with the shielding in weapon systems is, therefore, to reduce to a minimum the number of holes or gaps in the solid shielding of the missile system components and to reduce the coupling through the holes to an acceptable level. Fig. 4-4 illustrates proper and improper handling of a typical weapon system shielding problem.

In terms of the conservative shielding parameter defined in par. 4-1.1.1, the presence of holes in a solid shield affects both the power reflection term T_p and the attenuation term A. The A term which is associated with the power loss through the metal shield is not applicable to the power loss through the hole. The power reflection loss T_p which depends on the input impedance of the shield will change in the vicinity of the hole since the overall input impedance of the shield will be altered by the hole.

4-1.1.3 Shielding Tests

At present all tests designed to evaluate the performance of a shielding material are based, with the exception of shield-on/shield-off irradiation tests of a complete equipment, on a specified impedance insertion loss determination procedure. The output of a sensing antenna is recorded both before and after the insertion of the shield as the item is irradiated. This procedure is essentially designed to stimulate the conditions of the classical shielding effectiveness formulations and as such would be expected to give data in agreement with that formulation. However, the literature shows that many of the experiments yield data, especially at low frequencies, that cannot be easily explained by the classical formulation.

In any case, the shielding test results recorded in the literature are not applicable to the evaluation of the shielding protection provided by the shield in weapon system usage since the weapon system conditions will not conform to the test conditions.

4-1.1.4 Evaluation of Leakage Through Gaps or Holes in the Shielding

Gaps and holes in a weapon system shield are at present unavoidable. The coupling of electromagnetic energy through these holes or gaps depends on the incident wave impedance, the size and shape of the holes, and the complex contents of the shielded volume. The simplest example is shown in Fig. 4-5 where a rectangular hole exists through a solid metal shield. The hole is excited by an incident wave of impedance Z_w and terminated by an impedance Z_t that represents the unknown impedance that terminates the hole. This impedance is a function of the contents of the shielded volume.

Considerable work has been done on a simpler version of the problem that assumes the shield to be of perfectly conducting material of almost zero thickness and Z_t to be determined by absolutely empty space on the nonexcited side of the perfectly conducting plane. This problem has been treated at length and exact solutions for various shaped holes are available for an assumed transverse electromagnetic (TEM) incident wave. (Reference is par. 2-1.2.2 for a definition of the TEM mode of propagation.) The solutions take the form of expressions for the transmission coefficient of the hole T_c defined as:

$$T_c = \frac{W_T}{Ar\ P_i} \tag{4-16}$$

where

W_T = power transmitted, W
Ar = area of the hole, m^2
P_i = incident TEM power density, W/m^2

These solutions show that T_c is a maximum, and has values somewhere between 1 and 2, when the dimensions of the hole are comparable to the wavelength of the incident radiation. At higher frequencies T_c approaches one, and at lower frequencies T_c decreases rapidly. For instance, a circular hole has a maximum value of T_c of approximately 1.7 when the perimeter of the hole is approximately 1.5 wavelengths. Experimental results, for holes whose dimensions are larger than or

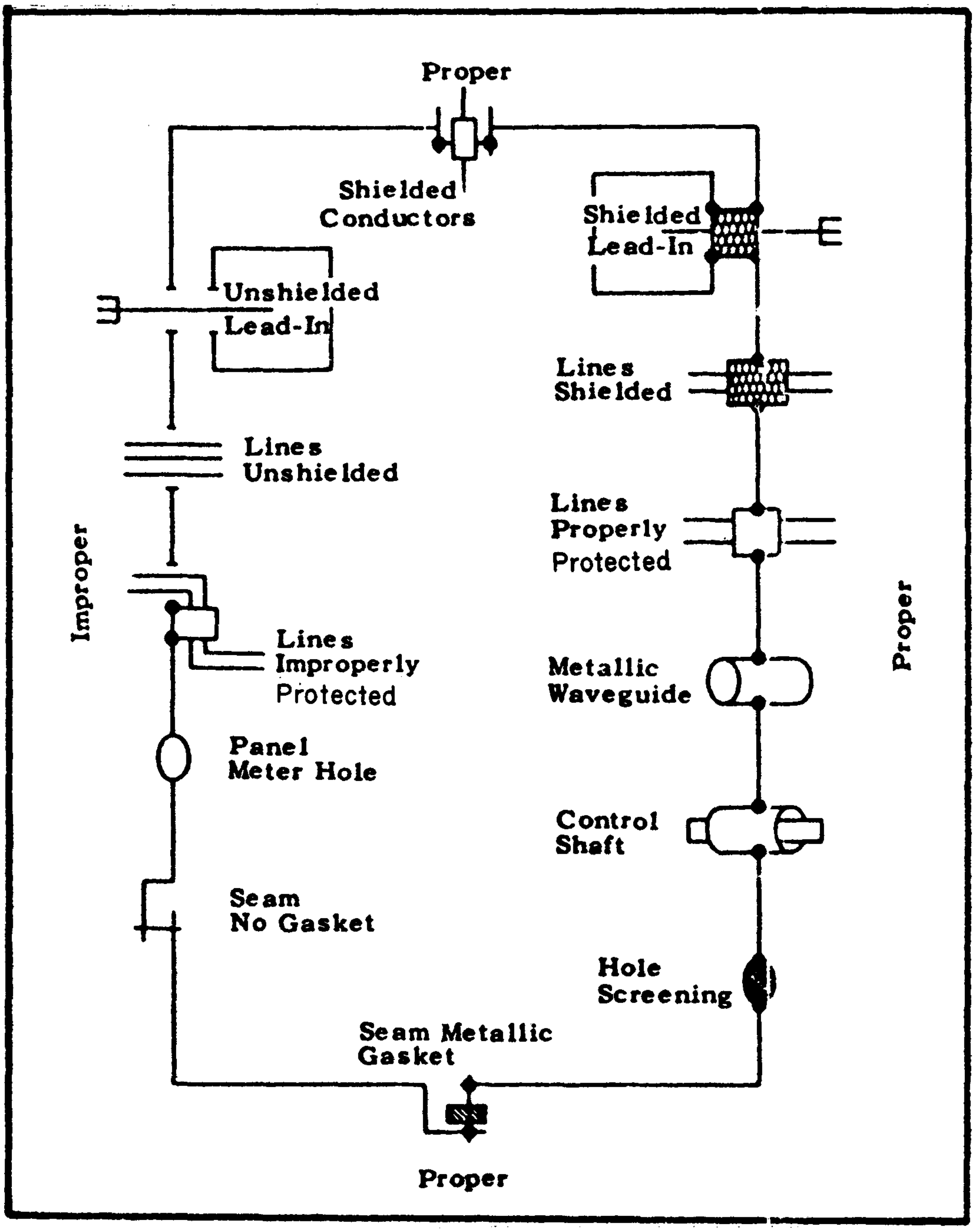


Fig. 4-4. Typical Shielded Compartment Discontinuities

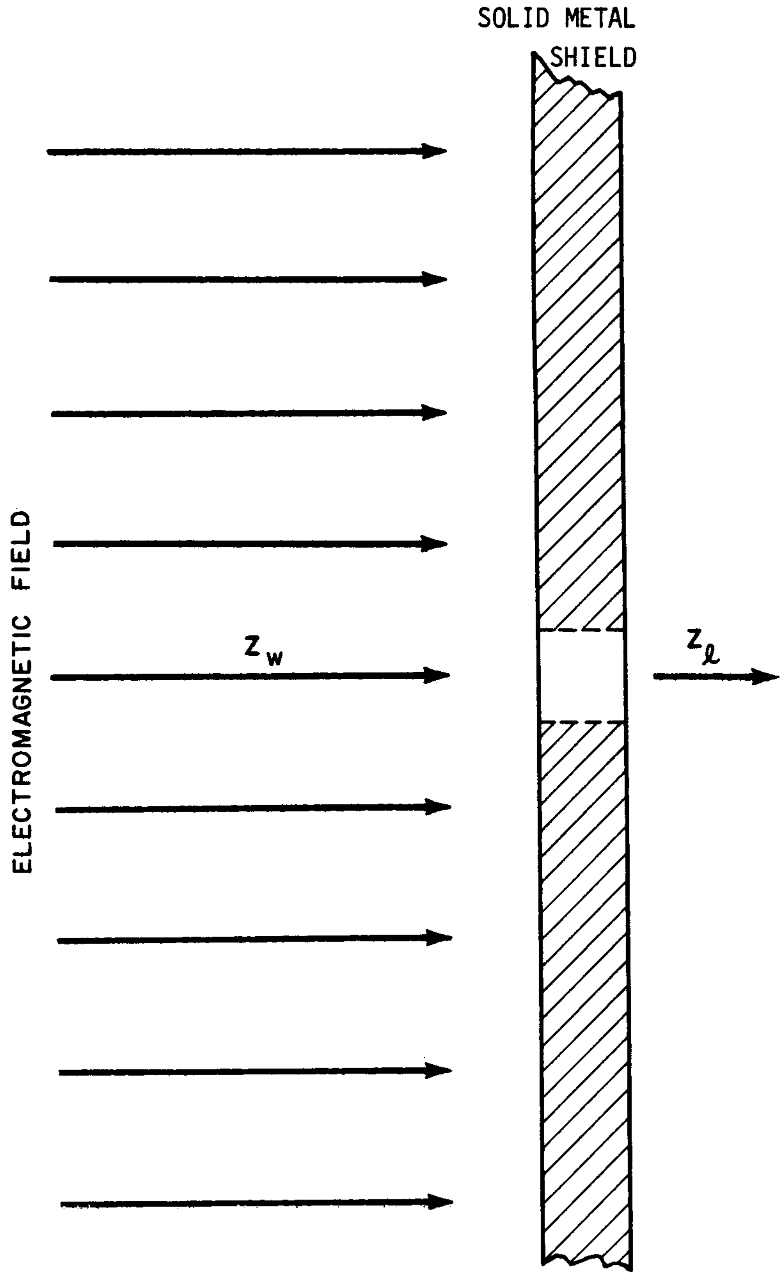


Fig. 4-5. Electromagnetic Field Impinging on a Solid Metal Shield Containing a Rectangular Hole

comparable to the incident wavelength, show good agreement with these solutions.

Limited theoretical work has been done that considers a non TEM-excitation. The results are roughly the same as those previously described. These results are not directly applicable to the weapon system protection problem even if it is assumed that the weapon system shield has infinite conductivity. First, the weapon system shield is of finite thickness and this imposes further restrictions on the solutions. Second, the impedance conditions immediately inside the surface of the weapon system shield will, especially at the lower frequencies, be influenced by the contents within the shield as well as the opposite sides which enclose the shield itself.

As far as it is known there are no available solutions to the hole leakage problem for finite thickness holes even assuming a known hole terminating impedance condition. Various works suggest, however, that the hole's finite thickness will reduce the coupling from that given by the simpler problem, although the coupling still depends upon the hole's terminating conditions. The use of waveguide below cutoff attenuation calculations for coupling through finite length holes is widely used but these calculations do not consider the actual problem of power transfer. In weapon systems usage, the hole terminating impedance conditions cannot be adequately predicted or measured except in exceptional circumstances.

The evaluation of leakage through holes in weapon system shields is thus an engineering estimation process. A procedure that is thought to be conservative, and yet not unduly restricting, is to assume that a perforated shield provides the same transmission loss T_p as a solid shield of the same material and that the holes transmit power to the interior of the shielded volume as

$$T_T = Ar\, P_T \qquad (4\text{-}17)$$

where

W_T = power transmitted, W
Ar = area of the hole, m^2
P_T = power density at the external interface assuming the shield is solid, W/m^2

This procedure is to be used only for holes whose maximum dimensions are much less than the incident wavelength. As an example, consider a square hole 1 cm (10^{-2} m) on a side through a surface of a cubical copper covered box with 1 m edges. Let the copper covering be fairly thin, say 10 mils, and the box be irradiated by a TEM field of 100 W/m^2 at 10 MHz.

T_p as defined by par. 4-1.1.1.1 gives the dB relation between incident power density and power density at the interface. Fig. 4-1 gives approximately 50 dB for these conditions. The leakage through the hole should then be, symbolically:

$$W_T = P_i\ (\text{down } T_p \text{dB}) \times \text{Area of Hole}$$

$$W_T = 100 \times 10^{-5} \times 10^{-4}$$

$$W_T = 10^{-7}\ \text{W}$$

where W_T is the power coupled through the hole.

The leakage through the solid metal portions of the box can be calculated by using the absorption loss of copper A, given by Fig. 4-3. It is approximately 10 dB per mil of copper at 10 MHz. Therefore, the power coupling through the metal is, symbolically:

$$W_{MT} = \left[(P_i \text{ down } T_p\ dB) \text{ down } A\ dB \right] \bullet \text{Box Area}$$

$$= 100 \times 10^{-5} \times 10^{-10} \times 6 \times 10^{\circ}$$

$$\cong 6 \times 10^{-13}\ \text{W}$$

where W_{MT} is the power transmitted through the solid metal.

If the dimensions of the hole are comparable to the incident wavelength the hole may be conservatively assumed to couple as

$$W_T = P_i A. \qquad (4\text{-}18)$$

For instance, in the previous example assume the frequency is changed to 10 GHz where the wavelength is 3 cm, then the power transmitted into the interior of the box is estimated at

$$W_T = 100 \times 10^{-4} = 10\ \text{mW}$$

and the power through the solid metal is negligible.

Holes in shields should be kept as small as possible. If a braided shield is used as part of an outer RF protection shield, the holes should be as few and as small as possible. Shields braided from metal ribbon achieve this objective much better than shields braided from round wire, therefore ribbon braided shields are preferred.

4-1.2 SHIELDING MATERIALS

4-1.2.1 Electrical and Physical Properties

The total protection provided by an RF shield for reasonable shield thickness, is degraded by the gaps,

seams, and holes in the shield, as has been stated. In consequence the choice of a metal for shield use should be determined by its ability to eliminate leakage at joints over the life span of the weapon system.

Where corrosion, for example, may affect seams, etc. (see par. 4-1.3.4); extreme care must be exercised. The electrical parameters of most commonly available metals provide adequate solid shield protection. In some special applications where the shield must perform unusually well or be very thin, it may be necessary to consider high permeability and/or high conductivity metals. The range of conductivities and permeabilities of common metals is given in Table 4-3.

Absorption loss A (in dB) varies directly as the square root of the relative permeability, relative conductivity product. At any one frequency, the transmission loss

$$T_p = \text{Constant} + \left(\frac{1}{2}\right)\log\left(\frac{G_R}{\mu_R}\right), \text{ dB} \qquad (4\text{-}19)$$

Therefore, an increase of relative conductivity G_R by a factor of 100 increases A by a factor of 10 and increases T_p by 10 dB. An increase of relative permeability μ_R by a factor of 100 also increases A by a factor of 10 but decreases T_p by 10 dB.

At times conductive epoxies and pastes, carbon loaded rubbers, and other similar conductive materials are utilized as shielding materials. The dc conductivity of these materials is often the only electrical parameter known. The amount of shielding protection provided by these materials is problematical and–in addition–strain, pressure, and decomposition are likely to degrade the shielding performance of such materials. Unless extensive tests are performed to determine conductivity as a function of frequency and shielding degradation as a function of time, the use of such materials should be confined to emergency measures.

4-1.2.2 Closing Metal Shields

Closure of gaps and seams in shielding requires the application of good electrical bonding techniques. Electrical bonding can be defined as the process of mechanically connecting certain metal parts so that they will make a low-resistance electrical contact (see par. 4-1.3.8). Good bonding is required to ensure that a system is electrically stable and relatively free from the hazards of lightning, static discharge, and electrical shock as well as to assist in the suppression of RF interference. Usually, the dc resistance of electrical bonds should be in the order of 0.0025 ohm.

Holes in the shielding that must pass unshielded power or control leads create a special problem. These unshielded leads, external to the shielded volume, can couple very large amounts of power into the shielded volume in comparison to the amount of power that directly penetrates the shield. Such leads as these must be decoupled with RF suppression devices to ensure adequate RF protection to the components within the shielded volume. Par. 4-4 describes applicable RF suppression devices.

4-1.2.2.1 Gaps and Seams

Gaps resulting from improperly bonded seams can lead to considerable RF leakage.

Bonds which result in gaps and degrade the shield's effectiveness are most commonly produced by poor spot welds or poorly spaced fasteners such as screws or rivets. See Fig. 4-39(D) for an illustration of gaps resulting from a poor spot weld.

4-1.2.2.2 Construction of Seams

Several configurations for seams between two metallic members within a weapon system are shown in Fig. 4-6 (see also par. 4-1.3.8.1). The preferred seam is a continuous weld around the periphery of the mating surfaces. The type of weld (other than spot welding) is not critical, provided the weld is continuous. In all cases, a continuous weld is desired since spot welding leaves gaps or slits. Table 4-4 summarizes, in order of preference, techniques for implementing permanent or semipermanent seams.

4-1.2.2.3 Overlapping Seams

An acceptable alternative technique is the overlap seam shown in Fig. 4-6(D). In an overlap seam, all nonconductive materials must be removed from the mating surfaces before the surfaces are crimped, and the crimping must be performed under sufficient pressure to ensure positive contact between all mating surfaces.

4-1.2.2.4 RF Impedance

Regardless of the type of seam used, the RF impedance of the seam must not differ appreciably from that of the materials being joined. If the RF impedance of the seam is relatively high, RF voltages can develop across the seam from skin currents, permitting RF energy to enter the shielded enclosure. It is sometimes necessary to use continuous welding of seams to ensure shielding effectiveness.

4-1.2.2.5 Recommendations

Seams that are properly bonded will provide a low impedance to RF current flowing across the seam. Wherever possible, mating surfaces of metallic members within a weapon system should be bonded together

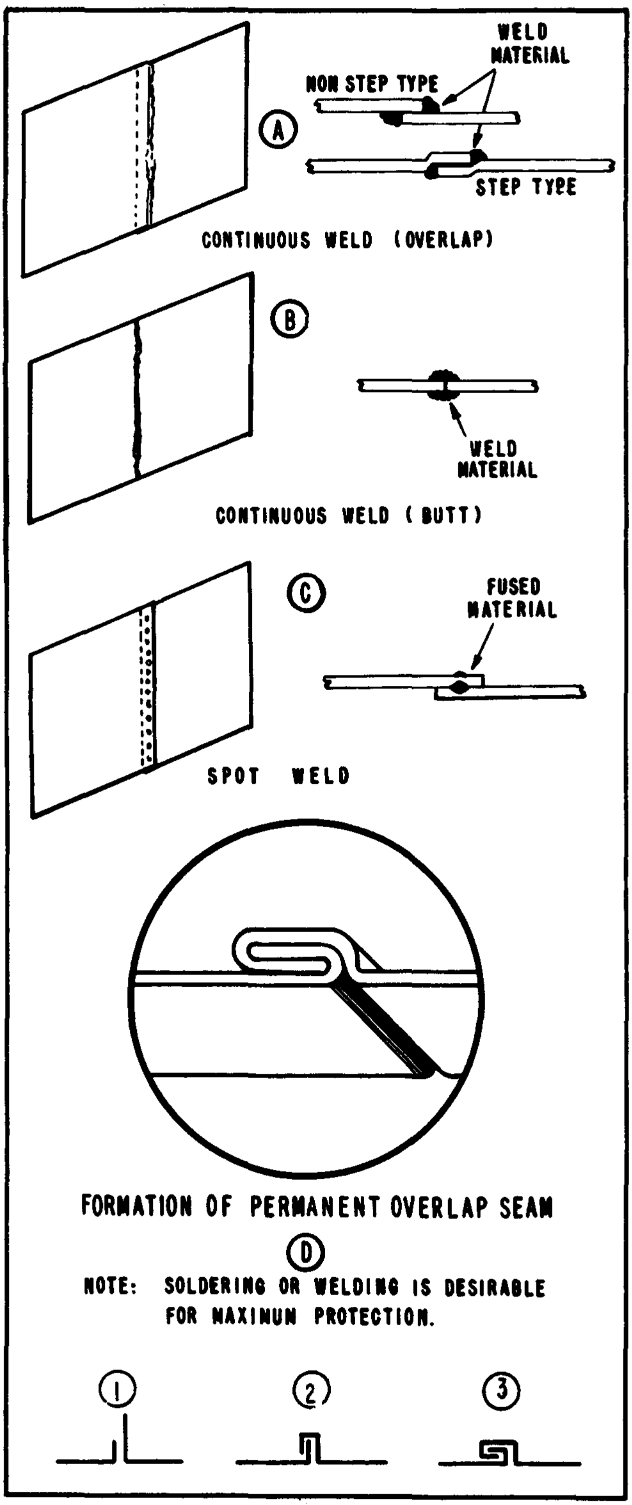


Fig. 4-6. Panel Seam Configurations

TABLE 4-4

TYPE OF SEAMS IN ORDER OF PREFERENCE

PREFERENCE	TYPE OF SEAM	REMARKS
1	Continuous weld	Best RF seam
2	Spot weld	Space weld joints less than 2 in. apart
3	Crimp seam	Use strong and lasting crimping pressure; pressure is maintained by spot welding

by welding, brazing, sweating, swaging, or metal-forming. To assure adequate and properly implemented bonding techniques, observe the following recommendations:

a. All mating surfaces must be cleaned before bonding.

b. All protective coatings having a conductivity less than that of the metals being bonded must be removed from the contact areas of the two mating surfaces before the bond connection is made. (The conductivity of coatings, such as anodizing materials, should be verified with the manufacturer whenever it is questionable.)

c. When protective coatings are necessary, design them so that they can be easily removed from mating surfaces. Since the mating of bare metal to bare metal is essential for a satisfactory bond, a conflict may arise between the bonding and finish specifications. It is preferable to remove the finish where compromising of the bonding effectiveness would occur.

d. Generally, protective metal platings such as cadmium, tin, or silver need not be removed. Coatings having poor conductivity destroy the effectiveness of a bond to produce a low impedance RF path.

e. Mating surfaces should be bonded immediately to avoid oxidation after protective coatings are removed.

f. The nonreplaceable portion of a bonded joint that must be formed by dissimilar metals should be a metal lower in the electromotive force series than its mate (see Table 4-10). When two dissimilar metals must be bonded, select metals that are close to one another in the electromotive force series.

g. Bolted sections may be used for temporary bonds. However, bolted sections could be bonded to ensure consistent contact pressure over an extended period of time. Shield material must be rigid enough to prevent buckling between contact points.

h. When bolts or rivets are used to make a bond, they should be applied first at the middle of the seam and then progressively applied toward the ends of the seam to prevent the mating surfaces from buckling. The protection provided by the joint seems to depend on the number of fasteners per linear inch, the pressure of the contacting surface, and the cleanliness of the two mating surfaces.

i. When pressure bonds are made, the surfaces must be clean and dry before mating and then held together under pressure to minimize the growth of oxidation due to moisture entering the joint because the joint may not be 100% moisture-tight. The periphery of the exposed joint should then be sealed with a suitable protective compound and, whenever possible, one that is highly conductive to RF currents.

4-1.3 APPLICATIONS

The protection of a weapon system from RF energy requires construction of an adequate shield, reducing coupling through the necessary openings in the shield, and design of internal circuitry to reduce coupling to sensitive components. The use of the RF suppression devices on any unshielded leads entering the shielded volume is also an important part of providing adequate RF protection. RF suppression devices are discussed in par. 4-4. This paragraph presents some of the techniques necessary to reduce coupling through the holes in the shield and also points out the problems associated with special applications.

4-1.3.1 External Structures

In many weapon systems the external metal case of the system can be utilized as an effective RF shield.

If the external skin of the weapon system is nonmetallic,then shielding protection must be provided by the equipment cases, containers, or specially designed protective structures which are used when the equipment is assembled, inspected, or serviced. The problems in design and construction of these shields are similar. Additional shielding from RF exposure is required even if the weapon system skin does provide a shield for itself because–in the servicing, inspection, and assembly operations–shielding is negated by breach of the external skin resulting from opening access doors, removing sections of the weapon for inspection, etc. The locations at which these assembly, maintenance, and inspection operations are performed must be carefully investigated by the designer to provide adequate RF protection there. If operational requirements dictate that the weapon system skin must be breached occasionally in RF active areas, the designer should require that the outer metallic skin still be constructed with RF protection in mind. The cost is usually minor and the advantages from an RF protection viewpoint are obvious.

4-1.3.2 Shipping Containers

Shipping containers carrying a weapon system or its components are an important part of the hardening against the effects of RF energy, lightning, and static electricity. These environments are particularly hazardous to electroexplosive devices (EED's) and to solid state devices which are found in most modern weapon systems (Ref 1). If the systems are to arrive at the launching site in operating condition (or even arrive there), then precautions are necessary to the process of packaging.

Some of the factors that may influence a package are shown in Fig. 4-7. While most of these factors are of little interest with respect to hardening against electrical phenomena, the figure does illustrate the magnitude of the packaging problem.

Part of the problem in packaging is to determine the level of excitation that will affect the subsequent performance of the system being packaged. It is known, for example, that shock, vibration, and heat experienced in normal shipping are of little consequence to the subsequent performance of EED's and solid state circuits. The shock levels are seldom greater than 10 times gravity (Ref. 2) and the temperatures that are encountered in shipping are seldom greater than 150°F. Both of these conditions are readily met by devices currently in use by the military, and portions of the MIL-STD tests through which these components must pass should screen out those that are not capable of withstanding this environment.

The electrical environment, on the other hand, can be a definite hazard unless specific steps are taken in shipping to allow for this environment. One reason that the electrical environment tends to be difficult to protect against is that it is undefined, as is discussed in par. 2-1, throughout the journey of the package.

One source of electrical problems associated with components is the unpackaging of EED's or the handling of MOSFET's (metal-oxide semiconductor field-effect transistors). Some of the packages used are constructed in such a way that withdrawal of the devices causes frictional static electricity to be generated. EED's have actually exploded during the withdrawal process and personnel have been injured (Ref. 3).

Packages that tend to generate static electricity are to be avoided. These are generally of the plastic film type. Some of them are difficult to recognize because the film of plastic is deposited on the inside of a metal foil bag. The plastic materials are convenient for packaging because they form a good moisture barrier and are easily heat welded.

To overcome this problem, a number of plastic manufacturers are using an antistatic plastic film. These appear to offer some protection against the effects of static, limiting, to some extent, the ability of the plastic film to generate static electricity. The status on these materials is still generally vague in respect to their use with EED's.

A more positive approach to the prevention of the effects of static is to wrap the devices in metal foil, followed if necessary by enclosure in a plastic envelope, although this procedure needs to be carried out with precautions. Unwrapping of this kind of a package must be carried out with the operator grounded and with disposal of the plastic bags from the work area prior to unwrapping the foil. Operations on foil-wrapped EED's must be carried out on a conducting grounded surface.

Shipping containers for components that may be influenced by electric energy should be made of metal rather than wood. Present interstate shipping regulations for explosive devices, however, call for wooden boxes (Ref. 4). In some instances the wooden box requirement is supplemented by having metal containers inside the wooden box. Thus the shipping requirements are met and the system and EED are enclosed in what amounts to a Faraday shield.

Radio frequency energy is effectively limited by the use of a complete Faraday shield. The classical field reduction afforded by copper and iron shields for reflection and absorption effects are shown in Fig. 4-8

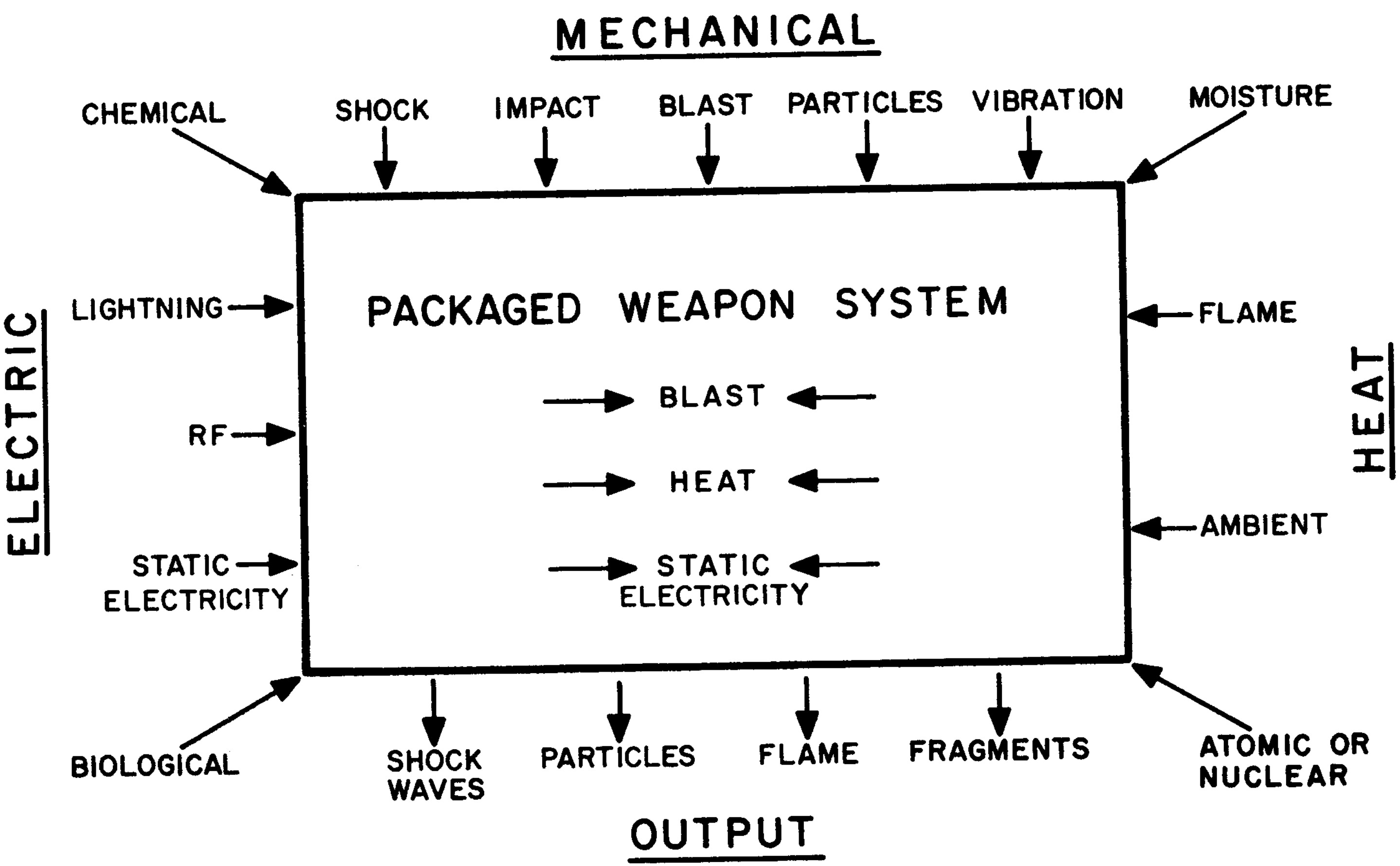


Fig. 4-7. Some of the Factors To Be Considered in Weapon System Packaging

(Ref. 5). In general, there is a relatively large loss associated with copper and iron containers. Reflection losses account for most of the elimination of energy at the lower frequencies. The reflection losses for the magnetic field increase with increasing frequency until a frequency of about 100 MHz is reached and then tend to level or to decrease slightly. The absorption loss behavior of iron and copper are different as shown by curves *A* and *B* in Fig. 4-8. Copper appears to be superior to iron for high reflection losses, but the reverse is true for absorption losses (up to 1 GHz). Thus it appears from this viewpoint that a copper-flashed iron would provide the ideal material for a shielded shipping container. Par. 4-1 discusses shielding in detail and should be consulted for a full understanding of applicable design equations.

energy from the environment both contribute materially to the amount of attenuation that is actually required for a given environment. Even in the absence of a Faraday shield for a container, it is well to follow several generally accepted practices in the use of EED's and sensitive solid state components:

a. It is generally accepted that the input leads to the EED should be short circuited.

b. If these leads are wires of any appreciable length, they should be twisted together. The reason for twisting is that induced currents in individual twists of the wire will tend to be out of phase with one another and the net result will be in cancellation of the induced electromotive forces of the individual loops.

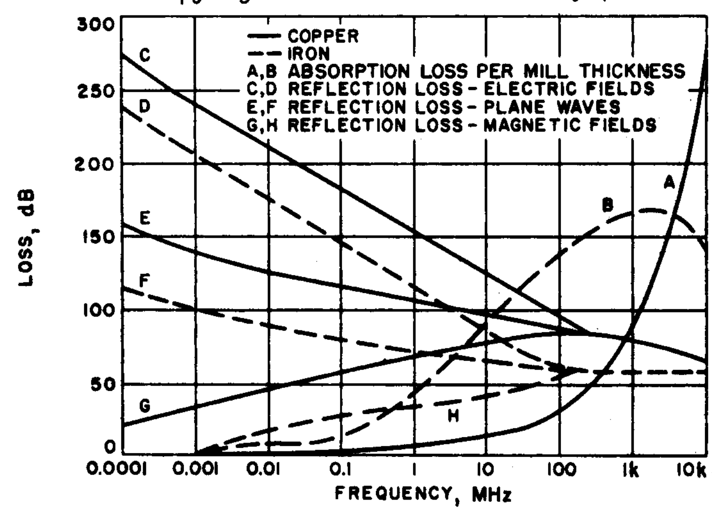


Fig. 4-8. Relative Shielding Effectiveness of Iron and Copper

Containers for sensitive devices need good electromagnetic seals at the closure junction (see par. 4-1.3.6). Tight fitting junctions assure that little leakage will occur past the joint. Gasket materials are currently manufactured that provide good contact under pressure.

Fig. 4-9 illustrates a shipping container that is used in transporting the warhead section of the LANCE weapon system. The case is made of soft steel to aid in low frequency and EMP protection. An RF gasket is used between the sections to ensure a good RF seal at the mating edges.

The sensitivity of the device contained in the package and the efficiency with which exposed leads can extract

There is one other shipping and storage problem peculiar to EED's. If one device in a package of many devices fires, then it is important that the remainder of the devices do not fire or, at a minimum, do not fire within a very short time interval. The additive effect of all of the devices firing in a very short time could result in severe damage to external systems. It is for this reason that dunnage is required in packages of EED's. A barrier effect is necessary to prevent propagation of an explosion. While there is little specific information on the means of designing an effective type of barrier, there is considerable information that has been obtained experimentally on the effect of various barrier materials on specific explosives. For high explosives,

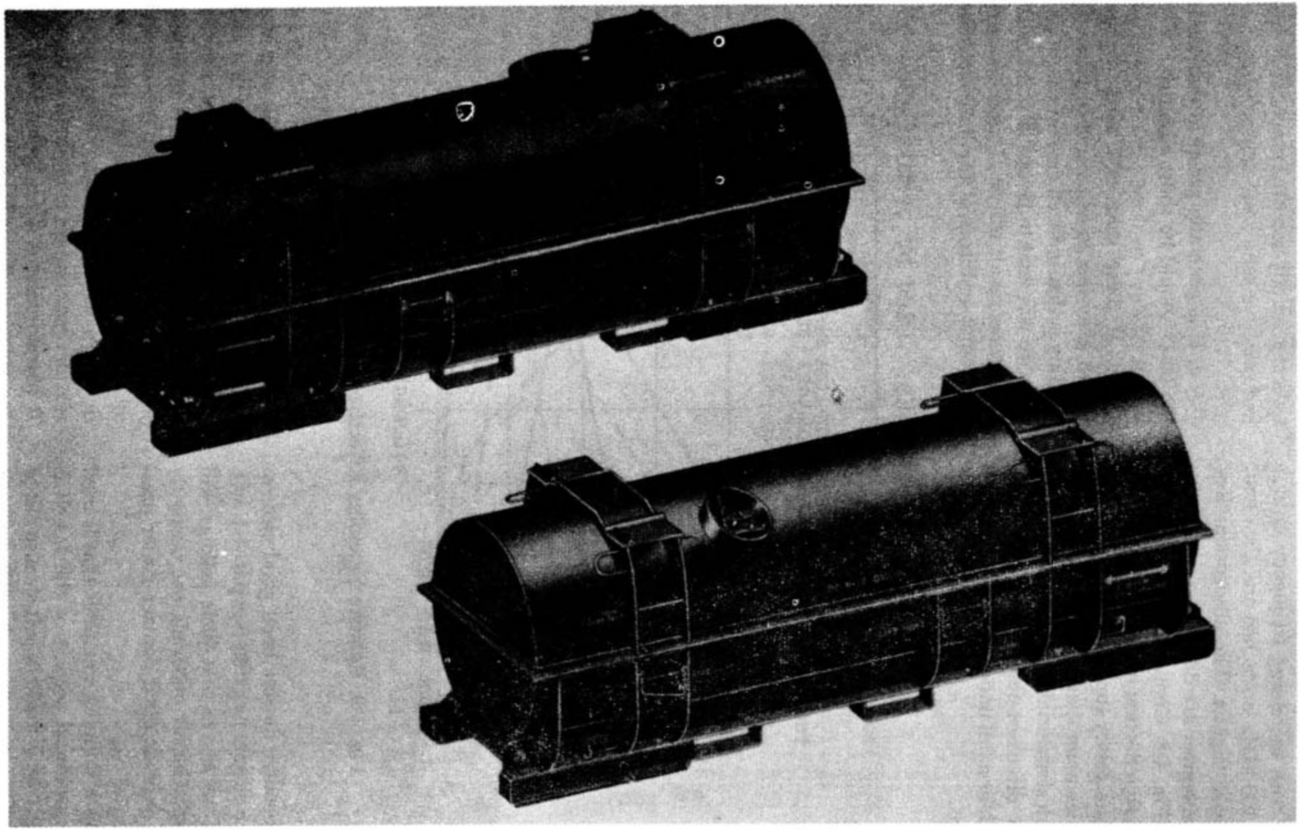


Fig. 4-9. XM511E1 Shipping and Storage Container

the most efficient barrier appears to be wood. Sawdust is in wide usage as a dunnage material. The requirement is that the high velocity particles and flash are absorbed and the shock wave is attenuated. Table 4-5 illustrates the gap distance for several materials and for several explosive types.

Little has been said about the packaging of low explosive devices or pyrotechnics. These generally create a higher heat output with the temperature of the reaction being maintained for a longer period of time. It would appear that additional barrier requirements for this type of a reaction would include thermal insulation and the use of a barrier material that would not burn or support combustion.

4-1.3.3 Test Equipment and Ground Support Equipment

Any test equipment or ground support equipment to be used with a weapon system in a potentially high electromagnetic environment should be designed to at least as high a level of RF protection as the weapon system itself.

In general, weapon system shields should be removed and common test equipment employed only in RF quiet areas. Special test equipment and ground support equipment should be equipped with completely shielded test and monitor cables. All unused jacks and plugs should be supplied with shielding caps. Permanent installations should use metal conduit for cable runs wherever possible.

4.1.3.4 Packaging of Components

The high density of electrical and electronic equipment in modern systems makes it difficult at times to place sensitive circuits or components away from interfering sources (Ref. 7). There are, however, certain precautions that should be observed when packaging equipment into a system. Assume for the moment that the system is protected against the external environment by proper shielding and the concern is now with its own internal environment. The major problem is then with transients which couple between circuits due to their close proximity. The examples which follow and which actually have occurred illustrate situations that should be avoided.

Fig. 4-10 shows a missile that has the sensitive guidance computer mounted on a metal bulkhead, while in the reverse side of the bulkhead is the firing unit for the EED's (stage separation, spin, etc.). When the firing unit was activated, the transient from this unit was coupled into the guidance computer and saturated it. The solution to this problem was to move the firing unit away from the guidance system.

The same firing unit also presented another transient coupling problem. In many systems where long runs of cables are involved, it is common practice to bind them in harnesses and then place them in metal conduits as was done in this system. The transient current for firing the EED peaked 2,000 A. The firing leads were shielded, twisted pair–yet the field from this transient coupled energy into adjacent shielded leads such that a two-volt spike appeared at the end of the cable and interfered with the operation of control circuits.

4-1.3.5 Cable Assemblies

Shield discontinuities in weapon systems should be avoided as much as possible to reduce the amount of RF leakage. Examples of areas where discontinuities

TABLE 4-5

SENSITIVITY FOR VARIOUS SPACER MATERIALS (WAX GAP TEST)[6]

Spacer Material	Average Penetration, in.			
	Tetryl	Comp. B	HBX	Pentolite
Air	5.04	1.21	0.93	5.01
Wood (oak)	1.39	1.04	0.93	1.47
Copper	1.69	1.17	0.86	1.92
Polystyrene	1.85	1.43	1.19	1.90
Acrawax B	1.89	1.46	1.28	2.08
Aluminum	1.90	1.51	1.33	2.05
Stanolind Wax	2.07	1.50	1.28	2.06

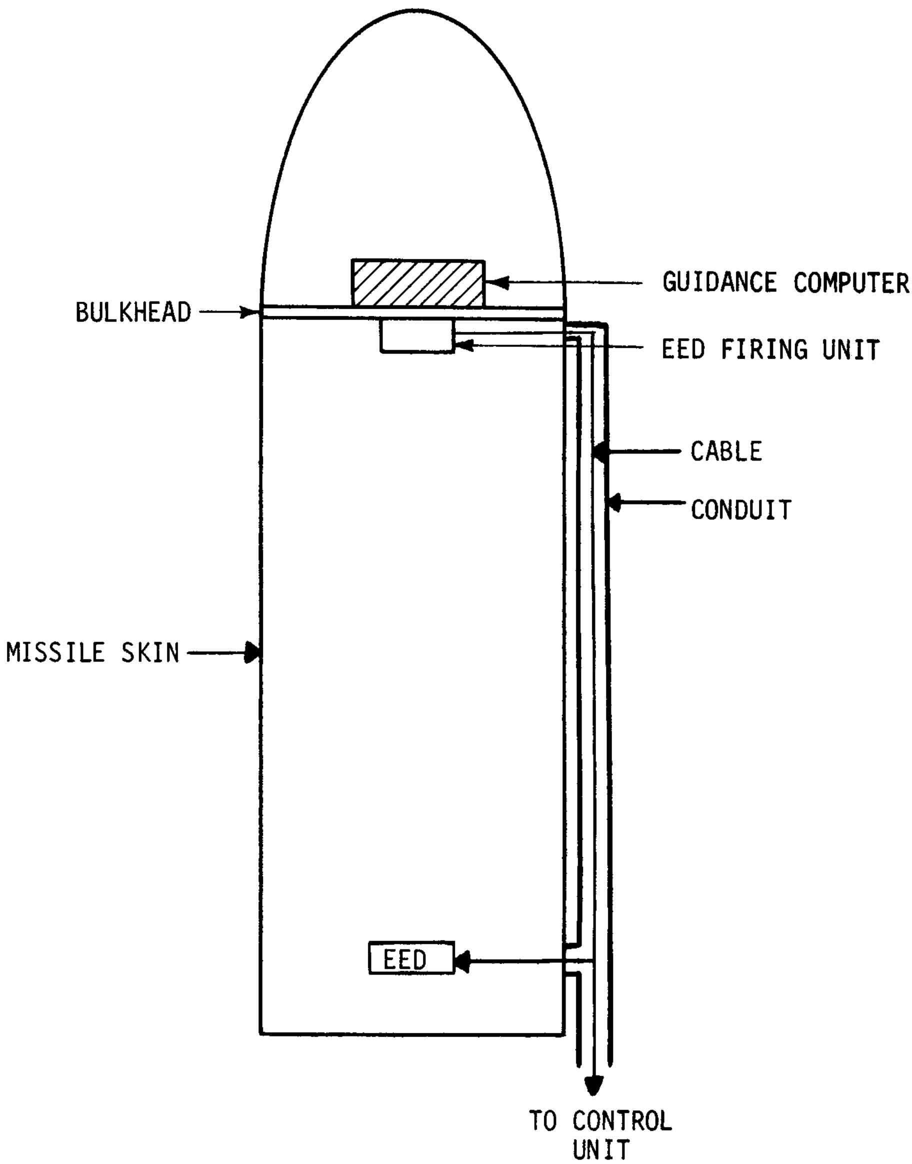


Fig. 4-10. A Missile Showing the Improper Location of Sensitive Components

can be eliminated by proper design practices are shield termination of cable assemblies, construction seams, and connectors. Some shield discontinuities are seemingly unavoidable, e.g., the points where conductors branch off. Where these occur, there are techniques that will ensure that the shielding effectiveness of the cable will not be reduced.

4-1.3.5.1 Cable Shielding

There are several methods for shielding cables. These include: (1) braid, (2) flexible conduit, (3) rigid conduit, and (4) spirally wound shields of high permeability materials.

Braid, which constitutes woven or perforated material, is used for cable shielding in applications where the shield cannot be made of solid material. Advantages are ease of handling in cable makeup and lightness in weight. However, it must be remembered that for radiated fields the shielding effectiveness of woven or braided materials decreases with increasing frequency and the shielding effectiveness increases with the density of the weave.

Conduit, either solid or flexible, may also be used to shield weapon system cables and wiring from the RF environment. The shielding effectiveness of solid conduit is the same, for RF purposes, as that of a solid sheet of the same thickness and material. Linked armor or flexible conduit may provide effective shielding at lower frequencies, but at higher frequencies the openings between individual links can take on slot-antenna characteristics, seriously degrading the shielding effectiveness. If linked armor conduit is required, all internal wiring should be individually shielded. Degradation of shielding conduit is usually not because of insufficient shielding properties of the conduit material but rather the result of discontinuities in the cable. These discontinuities usually result from splicing or improper termination of the shield.

Protection against RF energy, static electricity, and lightning is not the only shielding problem. Solenoids, or other devices associated with high inrush currents or incorporating switching devices that normally develop high-amplitude transients, can also prove a source of difficulty particularly where spacing between components is small. For protection against this type of energy, shielding materials with high permeability are desirable. These materials cannot be drawn into tubing because they lose their shielding properties when cold worked; therefore, an adequate shield is often developed by wrapping a continuous layer of annealed metal tape around the cable.

A typical application may involve shielding a cable of approximately 0.5 in. diameter, which has to be flexible in the final assembly. Annealed Mu-metal tape 0.001 in. thick and 0.25 in. wide wrapped in two layers would provide a suitable solution to this problem. The first layer can be spaced approximately 0.125 in. between convolutions, with the second layer overlapping the first layer to cover the gap between turns. The assembly should be covered with a protective rubber coating so that it may be flexed without losing its shielding effectiveness. A form of shielded cable using four counterspiral-wound bands of foil, Netic, Co-netic or their equivalent,* is also recommended. This construction is shown in Fig. 4-11. The strips can be from 0.25 in. to 1 in. wide. To minimize leakage between gaps, it is necessary to wind the material so as to permit spiral positioning along the length of the cable, with each following layer consisting of another spiral in the opposite direction. Successive layers of the tape, wound in this manner, ensure a minimum of gaps while permitting flexibility.

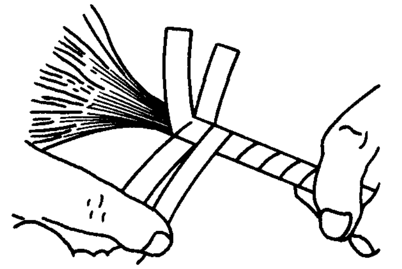


Fig. 4-11. Shielding by Using Bands of Foil

Such spiral-wound shielded cables are commercially available. A design engineer who needs a shield of this nature can procure the tape in foil form and, for evaluation purposes, fabricate a prototype shield for his own cables. A total of four wraps, or multiples of four, may be necessary for cables carrying appreciable current to prevent leakage due to magnetic saturation. For conductors carrying currents greater than two amperes, the first two layers should be Netic S3-6 foil or its equivalent; the remaining layers should be Co-netic AA foil or its equivalent. Netic and Co-netic foils and their equivalents are available from 0.002 to 0.007 in. in thickness and in various widths. After wrapping, the cable can be potted or encapsulated to prevent unraveling of the foil. Zipper tubing, as shown in Fig. 4-12, can also be used as an efficient means of mechanically holding the foil wraps in place. Zipper tubing is not recommended for cable shielding by itself. For additional

* Netic, Co-netic, Mu-metal, Unimag 80, Hi-Mu 80, and Hypernom are trade names of some materials which are used for shielding.

information on cables in general refer to AMCP 706-125, Engineering Design Handbook, *Electrical Wire and Cable.*

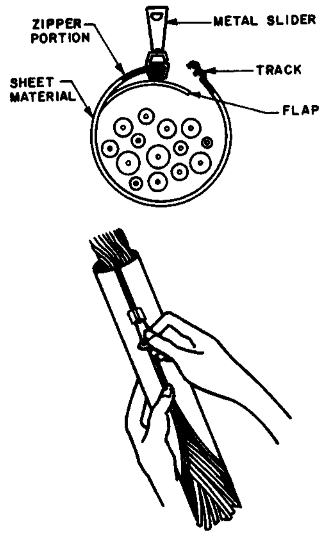


Fig. 4-12. Zipper Tubing

4-1.3.5.2 Types of Shielded Cables

The principal types of shielded cables that are available include shielded single wire, shielded multiconductor, shielded twisted pair, and coaxial. Cables are also available in both single and multiple shields in many different forms and with a variety of physical characteristics. Proper selection and application of appropriate cables for particular design requirements are necessary for the prevention of pickup of external energy. Table 4-6 presents a relative comparison of the four types of shields.

4-1.3.5.2.1 Shielding Effectiveness

If one were to refer to manufacturer's catalog of coaxial cable, he would discover that there is no reference made to shielding effectiveness. This is not an oversight but is the standard practice of the cable manufacturers. If the designer were to consult an electronics catalog, such as the *Electronic Engineers Master,* he will find that the fifteen cable companies who list their shielded cable specifications do not mention shielding effectiveness.

There are several reasons for not including these data in the manufacturers specification. First, there is no MIL-SPEC on shielding effectiveness; therefore, there is no way to report information that is compatible with one cable versus another. Second, the way in which the cable is used–i.e., its loading–affects its characteristics, e.g., MIL-C-7078B calls for the ratio of metal to open space in a shield to be 85-90 percent when in its normal position. When the cable is bent, however, the ratio changes depending on the radius of the bend. Also, the ratio can be altered when the shield is fastened to the back shell of a connector; e.g., a cable with a shield having an inner diameter of 0.375 in. If the shell diameter is larger, the cable will be spread, thereby lowering the metal to open space ratio. Third, the impedance of the cable's termination will also affect its shielding effectiveness.

4-1.3.5.2.2 Cable Capacitance

The designer should be aware that in addition to the increase in size and weight that shielding produces, the

TABLE 4-6
COMPARISON OF SHIELDED CABLES

	Copper Braid	Foil	Solid Conduit	Flexible Conduit
Shield Effectiveness (audio frequency)	Good	Exc.	Exc.	Good
Shield Effectiveness (radio frequency)	Good	Exc.	Exc.	Poor
Normal % of Coverage	60-95%	100%	100%	90-97%
Fatigue Life	Good	Fair	Poor	Fair
Tensile Strength	Exc.	Poor	Exc.	Fair

capacitance per foot also increases. This shunt capacitance of the cable can be important in some circuits and has to be considered. Fig. 4-13 shows the effect that shielding has on capacitance of various wires.

4-1.3.5.2.3 Current Rating

The current rating of the conductors used in cables is specified in MIL-B-5087B, *Bonding, Electrical, and Lightning Protection for Aerospace Systems.* A listing of specified current-carrying-capacity of conductors is reproduced in this handbook as Table 6-5.

4-1.3.5.3 Cable Specifications

In order to aid the designer in selecting the type of cable required and to ensure that the manufacturer delivers a qualified product, several cable specifications are available. The following five specifications are the most pertinent:

1. MIL-C-17D, *Cables, Radio Frequency, Coaxial, Dual Coaxial, Twin Conductor, and Twin Lead.*
2. MIL-C-7078B, *Cables, Electric, Aerospace Vehicle, General Specifications for.*
3. MIL-C-27500, *Cables, Electrical, Shielded and Unshielded, Aircraft and Missile.*
4. MIL-C-55021A, *Cables, Twisted Pair and Triples, Internal Hookup, General Specifications for.*
5. QQ-B-575a, *Braid, Wire, (Copper, Tin Coated, Tubular).*

4-1.3.5.4 Branches and Terminations

4-1.3.5.4.1 Branches

In many instances it is necessary to branch-out some of the conductors located inside a shielded cable. The junction so formed is usually referred to as a Y- or a T-type. It is very important that the integrity of the shield be maintained at this point, otherwise, the shielding effectiveness of the complete assembly can be seriously impaired. Fig. 4-14 illustrates a T-type junction that ensures the maintenance of shielding integrity. A solid metal sleeve is used as the junction between the shields and is soldered 360 deg to ensure minimum leakage.

Under no circumstance should a wire be brought out through a hole in the shield. This includes a shielded wire within the main shield. Soldering the two shields together at the point of penetration is not a satisfactory solution.

4-1.3.5.4.2 Terminations

The most common method of terminating a shielded cable is with a connector. When considering the shielding effectiveness of a cable assembly, the connector must be included since the various parts represent discontinuities in the shield. Even though there is mechanical contact with the cable shield through the outer ring of the mating connector, an adequate RF connection is not assured. Poor contact at these interfaces can be considered as gaps in the cable assembly. To ensure that the quality of the connectors used by the military services meet a minimum standard, the letters MS that prefix a connector part number are used to indicate an approved connector under the current Military Specification, MIL-C-5015.

One of the methods used to ensure a superior RF proof connector is to place spring contacts inside one portion of the connector (see Fig. 4-15) so that positive contact is made along the circumference of the mating

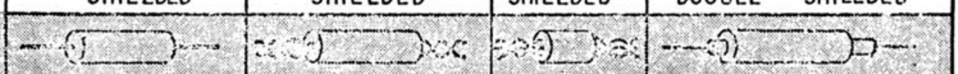
CAPACITANCE IN PICOFARAD PER FOOT												
TYPE	ONE WIRE SHIELDED				TWO WIRE SHIELDED				THREE WIRE SHIELDED		ONE WIRE DOUBLE SHIELDED	
CONFIGURATION												
WIRE SIZE	16	18	20	22	16	18	20	22	20	22	22	22
CONDUCTOR TO SHIELD pF/ft	89	91	74	98	68	65	64	62.5	60	52	98 (CONDUCTOR TO INNER SHIELD)	340 (INNER SHIELD TO OUTER SHIELD)
					(EITHER CONDUCTOR TO SHIELD)				(ANY CONDUCTOR TO SHIELD)			
CONDUCTOR TO CONDUCTOR pF/ft					42	39.5	38	36.5	36	30		
NOTE: DATA FOR USE IN CALCULATING THE EFFECTS OF CAPACITANCE IN SUBSYSTEMS WIRING.												

Fig. 4-13. Capacitance of Various Shielded Wires[8]

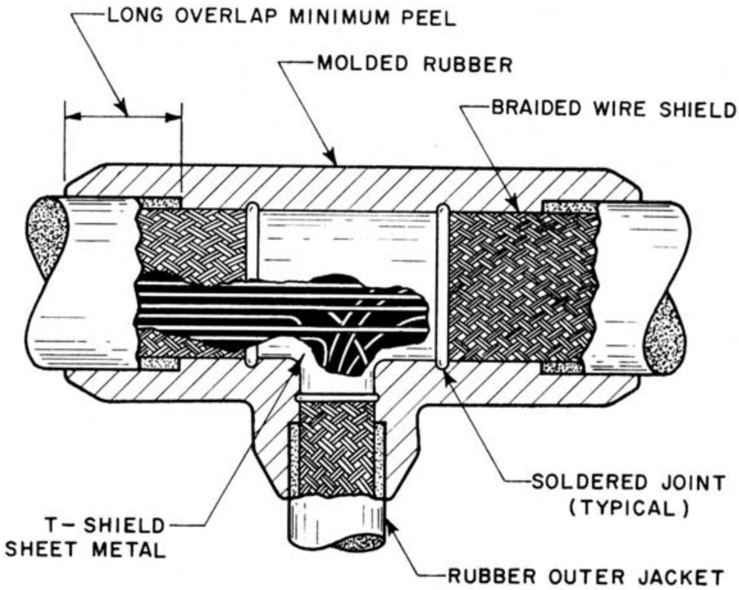


Fig. 4-14. T-junction

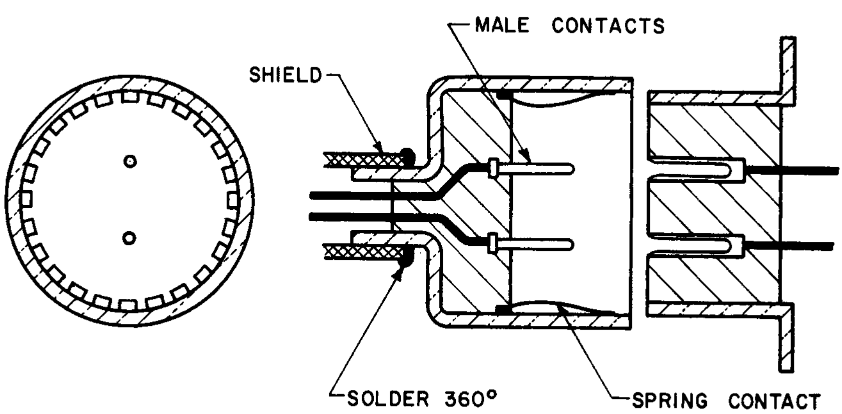


Fig. 4-15. RF-proof Connector

parts. These contacts are extended so that the shell of the connector mates before the pins make contact on assembly of the connector and breaks after the pins on disassembly. A connector which meets these requirements is available under MIL-C-27599 and is the preferred type to be used in RF-proof designs.

Fig. 4-16 illustrates the type of connector that should be used when a shielded cable assembly contains individual shielded wires. The practice of pigtailing these shields and connecting them to one of the pins is not recommended. The individual shields should be connected to coaxial pins specifically adapted for this purpose. MS32-101, shown in Fig. 4-17, is an example of a connector that has twelve contacts, two of which are made to handle shielded wires.

When considering the interconnection of subsystems, it is not always desirable to use connectors in the cabling between them. In this situation, it is necessary to find some other method of terminating the cable without affecting its RF integrity. The practice of inserting the shielded cable through a hole in the metal case of the terminating subsystem should be avoided. Even if the shield is soldered at this point, the practice is not acceptable. The technique illustrated in Fig. 4-18 is one method that can be used without affecting the shielding effectiveness.

4-1.3.5.4.3 Connector Specifications

In order to aid the designer in selecting the type of connector required and to ensure that the manufacturer delivers a qualified product, several connector specifications are available. The following six specifications are the most pertinent:

1. MIL-C-5015D, *Connectors, Electric, "AN" Type.*
2. MIL-C-26482D, *Connectors, Electric, Circular, Miniature, Quick Disconnect, Environment Resisting.*
3. MIL-C-26500C (USAF), *Connectors, General Purpose, Electrical, Miniature, Circular, Environment Resisting, Established Reliability.*
4. MIL-C-27599, *Connector, Electrical, Miniature, Quick Disconnect (for Weapon Systems) Established Reliability.*

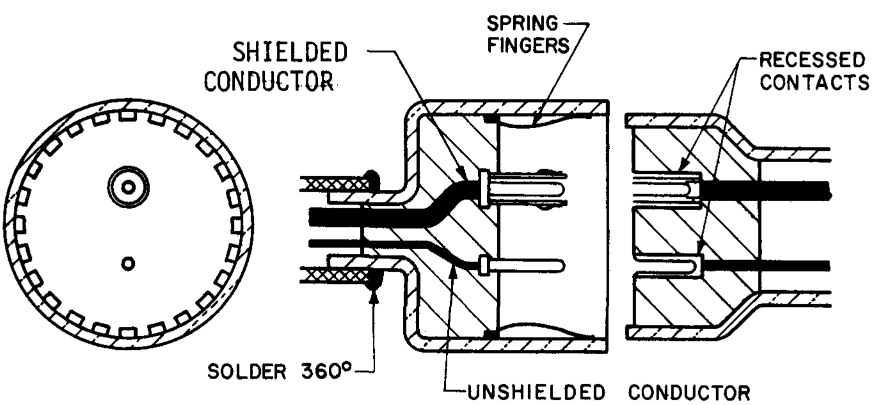


Fig. 4-16. Connector for Shield Within a Shield

5. MIL-C-38300A (USAF), *Connectors, Electrical, Circular, Multicontact, High Environment, Quantitative Reliability, General Requirements for.*
6. MIL-C-39012A, *Connectors, Coaxial, Radio Frequency, General Specifications for.*

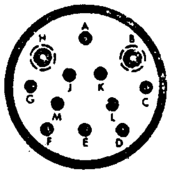


Fig. 4-17. Typical Connector for Handling Shielded and Unshielded Wires

4-1.3.6 Access Doors and Lids

Breaks in the outer metal skin of a weapon system can result in RF susceptibility problems. Breaks should be held to an absolute minimum compatible with other overall requirements on the system. If a break or joint

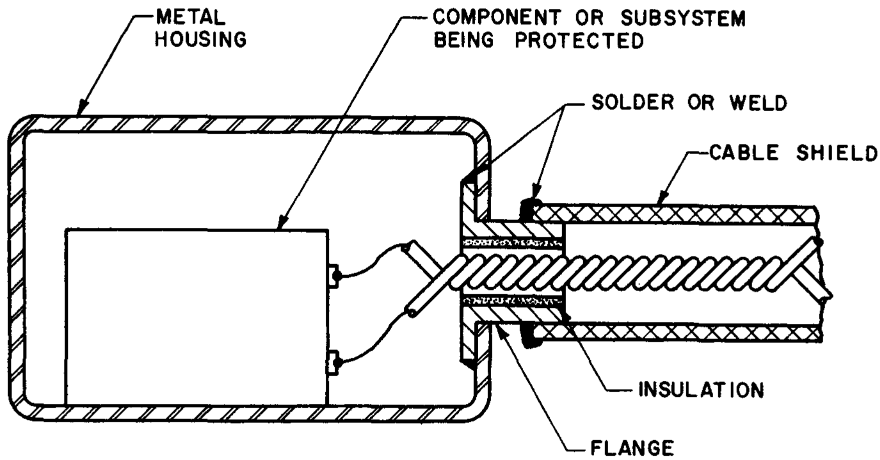


Fig. 4-18. Method of Terminating Shielded Cable Without a Connector

is unavoidable, then the type of closure or joining used is extremely important to the weapon system's overall susceptibility.

Often the weapon system designer must provide access to the electronic equipment located inside the system. The equipment itself also requires the use of doors or lids to facilitate servicing. In terms of RF effects, these access doors and lids represent breaks in the metal shield, and thus affect the susceptibility of the weapon system to radio frequency energy, static electricity, and lightning.

Wherever a junction appears between two surfaces, whether it be a door or a joint, special care must be exercised to prevent it from leaking RF. This is true whether the object is to confine RF within an enclosure or to prevent extraneous interference from entering an enclosure. A great deal of research has gone into this problem by persons concerned with radio frequency or electromagnetic (RFI/EMI) interference, where RFI/EMI is defined as *any radio frequency or electromagnetic signal that causes an undesirable response in the system under consideration.* Since most of the data available are obtained from RFI/EMI studies, it is convenient to discuss the problem from a RFI/EMI standpoint. The designer should remember, however, that the RF field densities his weapon system must be hardened against are usually several orders of magnitude higher than those that generate RFI/EMI.

The definitions of terms specifying shielding effectiveness in RFI/EMI terminology are compatible with simple measurement techniques and relate variables associated with a particular set of measurement conditions. There is little justification for assuming that the results apply to the actual protection provided a weapon system in its tactical environment except for conditions that are very close to those in which the measurements were made.

There are two basic elements to the problem: electrical and mechanical.

4-1.3.6.1 Electrical Aspects

Three items are commonly used when rating RFI/EMI shielding ability: (1) attenuation A, (2) insertion loss IL, and (3) total shielding effectiveness SE where

$$SE = A + IL \tag{4-20}$$

4-1.3.6.1.1 Attenuation

Attenuation is defined as the ability of a material to reduce the transfer of RF energy when the material is inserted in the path of the energy transmission. If P_T is a constant transmitted power from a transmitter, then P_{R1} is the received power without any shield in the path between transmitter and receiver. P_{R2} is the power at the receiver located inside a metallic enclosure where no RF gasket or other means of shielding is used. The decrease in signal strength due to the material, expressed in decibels, is the theoretical attenuation of the material (Ref. 9).

$$A = 10 \log \left[\frac{P_{R1}}{P_{R2}}\right] \tag{4-21}$$

4-1.3.6.1.2 Insertion Loss

Insertion loss is that loss of radio frequency leakage due to the insertion of shielding material. This loss can be determined in the following manner. A constant level signal source is placed in an enclosure and the opening in the enclosure is gasketed with shielding material which is inserted under the pressure

recommended by the manufacturer. The value of the received signal is observed at the receiver. The shielding material is then removed and a variable attenuator, located between the receiving antenna and the receiver, is adjusted until the receiver's output coincides with the readings obtained with the shielding material in place. The value of this attenuation, expressed in dB, is the insertion loss.

4-1.3.6.1.3 Total Shielding Effectiveness

Total shielding effectiveness (Ref. 10) is the decrease in RF leakage, due to the combination of enclosure and gasketing, expressed in decibels.

These definitions are specialized meanings of the terms as applied to shielding discussion. Reference is made to par. 4-3.5 for a theoretical discussion.

4-1.3.6.2 Mechanical Aspects

If a gasket material is selected properly and is applied properly, electrical requirements will usually be satisfied; but it must be noted that there are three basic design parameters involved in the mechanics of the gasketing problem (Ref. 11). These are: average pressure in the gasket, gasket height, and total joint unevenness.

Fig. 4-19 shows the change in insertion loss due to change in pressure on the gasket. The value of 20 psi is an average value (after many tests with various materials) at which additional pressure does not produce much additional insertion loss (Ref. 9). The type of joint being gasketed also affects the gasket height computations, because RFI/EMI gaskets take a degree of compression set. Joints are classified in three categories:

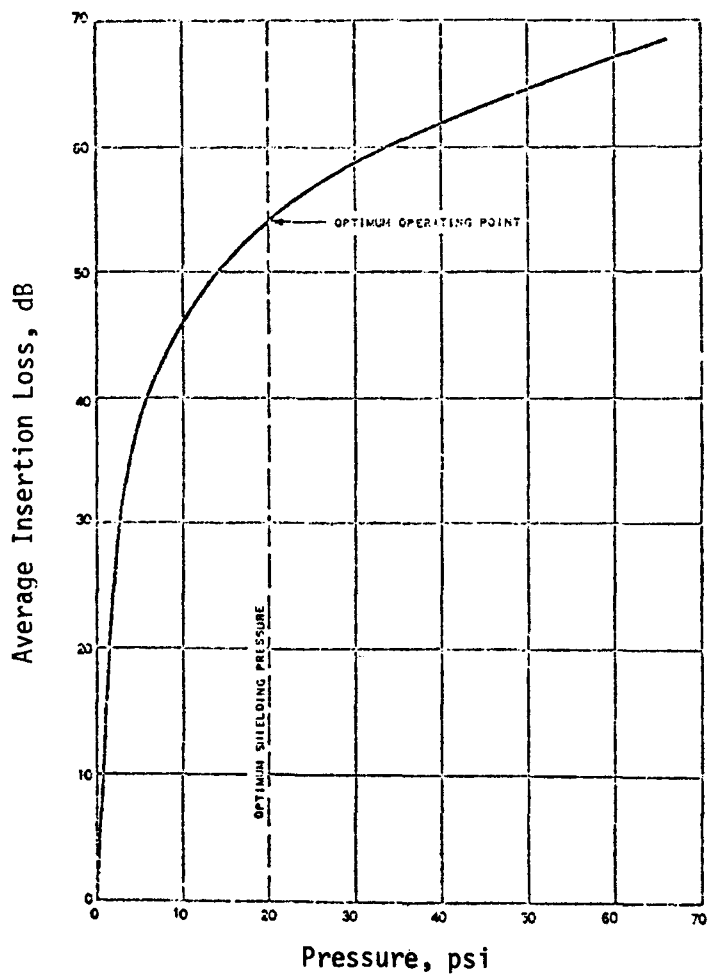


Fig. 4-19. Insertion Loss vs Pressure for Resilient Metal Gasket

(1) *Permanently closed joints.* In this situation compression set is of no concern. If the joint is opened for maintenance, a new gasket should be used for resealing.

(2) *Reclosable fixed-position joints.* When mating surfaces always match, as with hinged doors, compression set creates a constant, reduced "uncompressed" height. This makes it possible to recycle gaskets continuously if sufficient thickness is built into the original gasket.

(3) *Interchangeable joints.* Symmetrical coverplates, for example, rarely are replaced in the exact position of previous closure. Thus a point of minimum compression may coincide with a point of maximum gasket compression set. This type of joint requires the greatest thickness of gasket when originally installed to reduce the amount of compression set. Interchangeable joints should be avoided in RF-proof designs.

The third design parameter, total joint unevenness, is important because it is used for the determination of the gasket height. Fig. 4-20 shows how the total joint unevenness Δd_h is determined. A simple rule of thumb determines the minimum gasket height for the three categories:

Category (1) Gasket height equals $2 \times \Delta d_h$
Category (2) Gasket height equals $3 \times \Delta d_h$
Category (3) Gasket height equals $4 \times \Delta d_h$

Another rule of thumb that applies specifically to fluid gaskets can also be applied to conductive gaskets: the greater the compressibility, the greater the sealability. This principle is illustrated in Fig. 4-21 which depicts a simulated joint and three gaskets. Fig. 4-21(A) is the joint to be closed. Gasket 1 is one half the height of 2 and 3, and is very resilient; gasket 3 has the same resiliency as 1; and gasket 2 is harder than 1. For simplicity, assume gaskets 1 and 3 have twice the resiliency of 2. They compress 50 percent under the force $\overline{F}$ applied to the joint, while 2 compresses only to 75 percent of original height. Fig. 4-21(B) shows gasket 1 compressed to 50 percent at the point of maximum

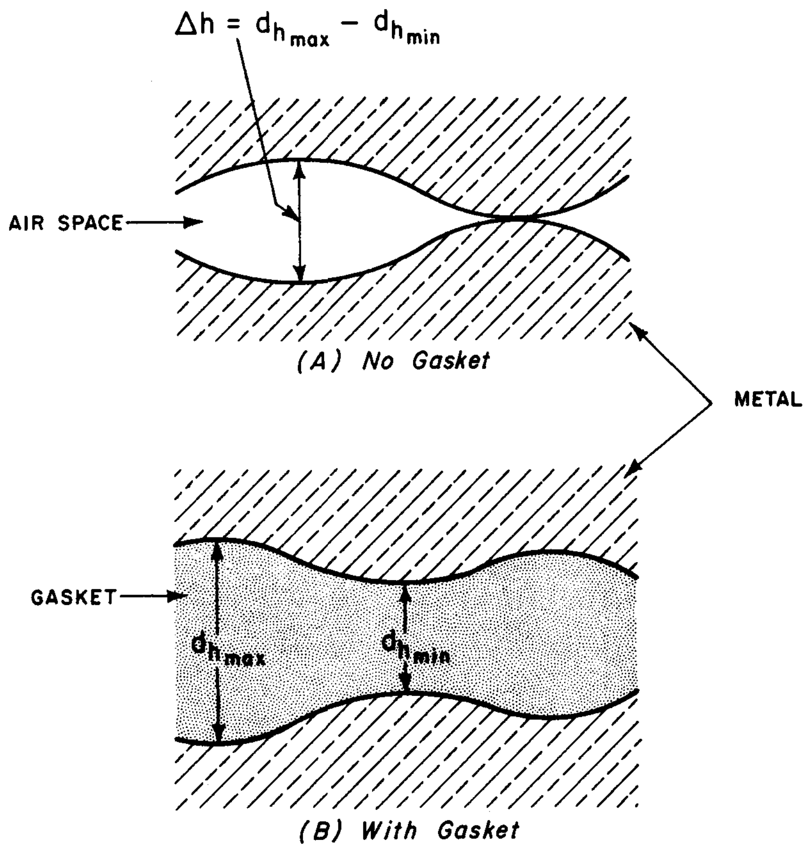


Fig. 4-20. Typical Mechanical Characteristics of a Resilient Metallic Gasket

compression and is not sufficient to seal the joint fully. Gasket 2 is then inserted (Fig. 4-21(C)) but, because it compresses only 25 percent under the same force, its greater height does not result in greater sealability. In Fig. 4-21(D) gasket 3 is compressed 50 percent, the same percentage as 1, since they are equally resilient. Because 3 is twice as thick as gasket 1, the same percentage of compression results in twice the actual compression, which is enough to effect the seal. Fig. 4-21(D) illustrates the basic axiom of gasket design; the gasket must be compressible and thick enough to conform to the irregularities of both surfaces under the applied force.

4-1.3.6.3 Material Selection

The classical shielding effectiveness equations for solid metal shields indicate that shielding performance depends on the permeability and the conductivity of the metal used as a shield. The same type of behavior can be expected, in a general way, from gasket material. The common procedure for selection of a gasket material is to select a material that would perform adequately as a solid shield in the frequency range and field conditions being considered. For example, if a gasket is to perform adequately in high magnetic fields at low frequencies, a material having a high permeability is usually selected.

The absorption loss (attenuation) of various materials at 150 kHz is given in Table 4-3. Study of this table shows that Mu-metal and Permalloy, whose permeabil ity is approximately 80,000, offer the highest attenuation at low frequencies to both magnetic and electric fields. These theoretical attenuations cannot be obtained if the material is driven into magnetic saturation; however, in gasket material selection this fact is usually ignored. In selecting a gasket material, the several major points to consider are:

a. Material should be compatible with mating surface.

b. Material should be corrosion resistant.

c. Material should be ferrous if intended for attenuating low frequencies.

d. Material should have good physical properties.

e. Material should have the highest possible conductivity compatible with its use.

The relative properties of three widely used knitted wire mesh materials are shown in Table 4-7.

Various materials have been used to combine resiliency and conductivity. Some of the more common materials are tabulated in Table 4-8 with their chief advantages and chief limitations.

There is available to the designer various manufacturers' handbooks and catalogues which illustrate the form and type of gasketing material the manufacturers can supply along with specific information as to mechanical, electrical, and corrosion properties of the gasket materials. The list includes the following:

a. Primec Corporation, Los Angeles, California: "electroknit" mesh, strips and gaskets, monel, aluminum, and silver plated brass.

b. Technical Wire Products, Inc., Cranford, New Jersey: strip matting, formed gaskets, shielding tape, fluid and shielding gaskets, felts, monel, aluminum, silver plated brass (Ref. 12).

c. Magnetic Metals Company, Camden, New Jersey: tubing, tape, and foil. Nickel iron alloys, silicon iron alloys, low carbon steel, copper.

d. Metex Corp., Edison, New Jersey: metallic sheath, honeycomb panels, feltex material, mesh strip, knitted wire. Aluminum, monel, silver-plated brass.

4-1.3.6.4 RF Gasket Design

When it is necessary to join several parts of a complete shield, the first consideration should be to minimize the number of joints. The next most important requirement is that a continuous metal to metal contact be maintained along the joints. To achieve this, the two surfaces in contact should be free of oxides, grease, dirt, and warping. If bolts or screws are used, a sufficient number are required to ensure high pressure at contact points furthest away from the bolts or screws (see par. 4-1.3.8.1.2).

Lack of stiffness of mating members produces distortion of mating surfaces, which results in bulging and insufficient pressure for maintaining good electrical contact. The design of these joints can be facilitated by the use of conductive gaskets. Such gaskets include textile gaskets and knitted wire mesh which are available in many different materials such as copper, monel, silver-plated brass, aluminum, and beryllium copper (see par. 4-1.3.6.3 for company listings). These gaskets can be combined with or imbedded in rubber or plastic to serve as water-, air-, and oil-seals as well as impenetrable interference shields. Examples of typical mounting methods are shown in Fig. 4-22, and various available configurations of gaskets are shown in Fig. 4-23.

Another type of gasket frequently used (Fig. 4-24) is fingerstock. This is a multiple joint spring-loaded contact with serrated fingers, which is a very efficient method of obtaining continuity. The serration gives enough spring pressure at the points of contact for electrical continuity. Materials used for fingerstock include beryllium copper, phosphor bronze, sheet metal,

TABLE 4-7

PROPERTIES OF TYPICAL GASKET MATERIALS[14]

Gasket Material	Corrosion Resistance	Compatibility With Aluminum or Magnesium	Conductivity Intrinsic	Conductivity Contact	Conductivity In Presence of Corrosion	Resistance To Set	Tensile Strength	Surface Hardness
Monel	1	2	3	2	1	2	1	1
Silver-Plated Brass	2	3	2	1	2	1	2	2
Aluminum	3	1	1	3	3	3	3	3

where 1 is the most desirable material
2 is a compromise
3 is the least desirable material

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TABLE 4-8
CHARACTERISTICS OF CONDUCTIVE GASKETING MATERIALS

Material	Chief Advantages	Chief Limitations
Compressed knitted wire	Most resilient all-metal gasket (low flange pressure required). Most points of contact. Available in variety of thicknesses and resiliencies.	Not available in sheet form (Certain intricate shapes difficult to make). Must be 0.040 in. or thicker.
Aluminum screen impregnated with neoprene	Combines fluid and conductive seal. Thinnest gasket. Can be cut to intricate shapes.	Very low resiliency (high flange pressure required).
Soft metals	Cheapest in small sizes.	Cold flows, low resiliency.
Metal over rubber	Takes advantage of the resiliency of rubber.	Foil cracks or shifts position. Generally low insertion loss yielding poor RF properties.
Conductive rubber	Combines fluid and conductive seal.	Practically no insertion loss, giving very poor RF properties.
Contact fingers	Best suited for sliding contact.	Easily damaged. Few points of contact.

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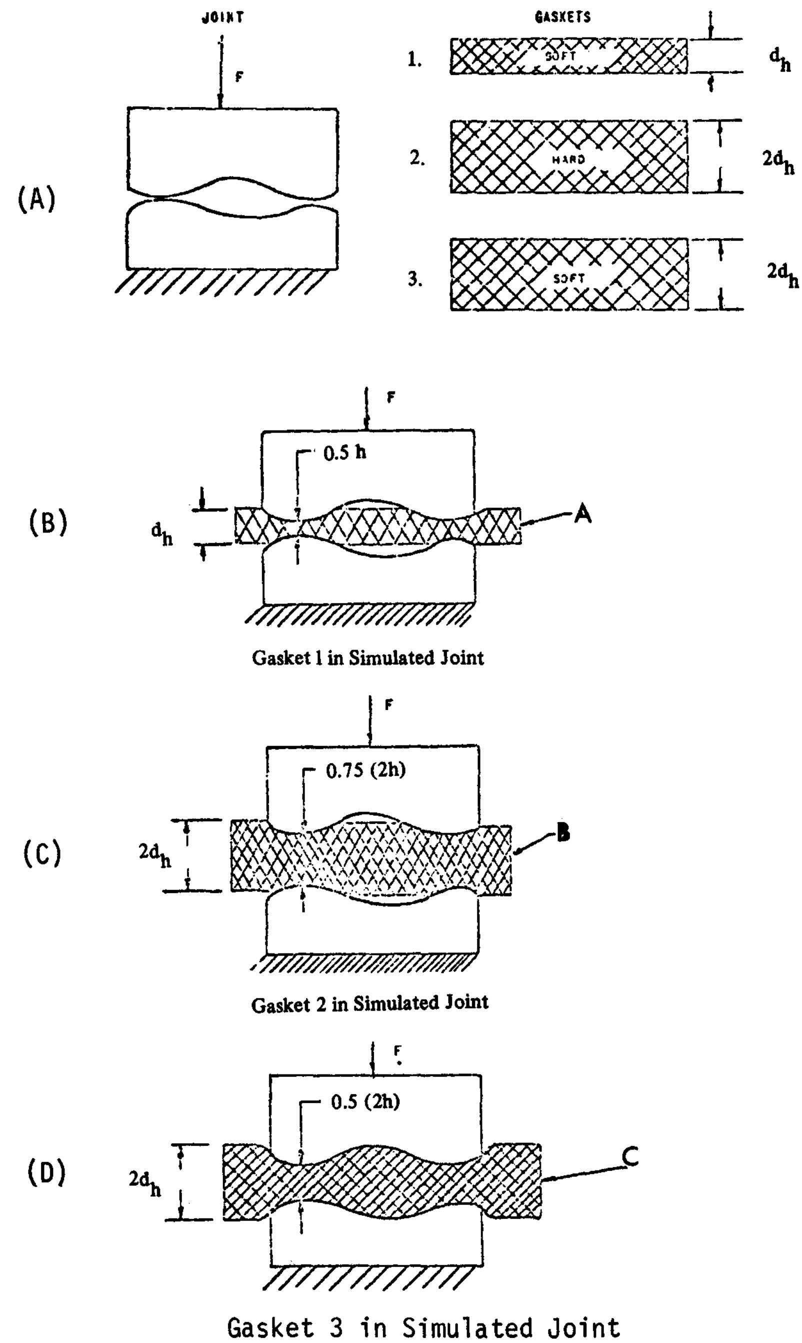

Fig. 4-21. Gasket Compressibility vs Sealability[13]

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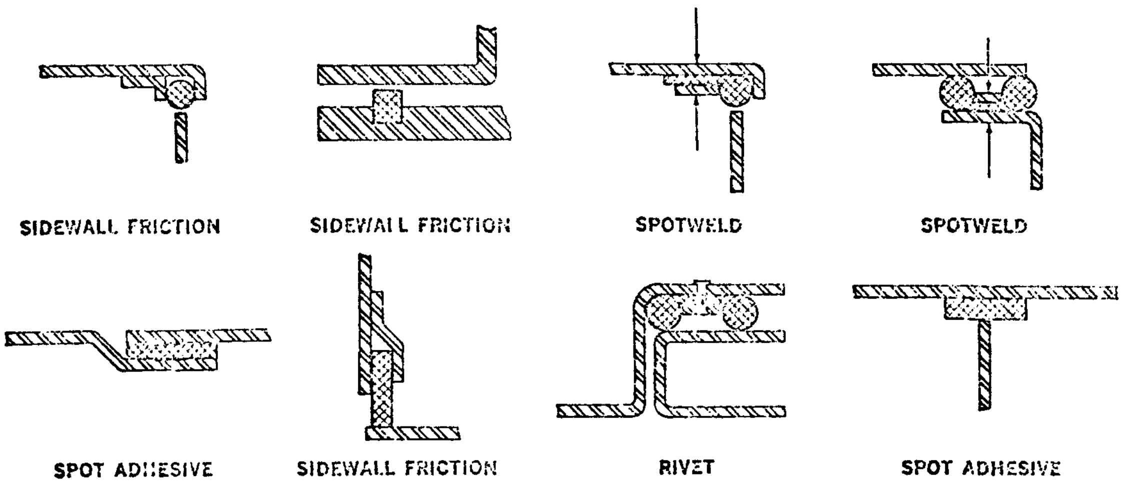

Fig. 4-22. Typical Mounting Methods[15]

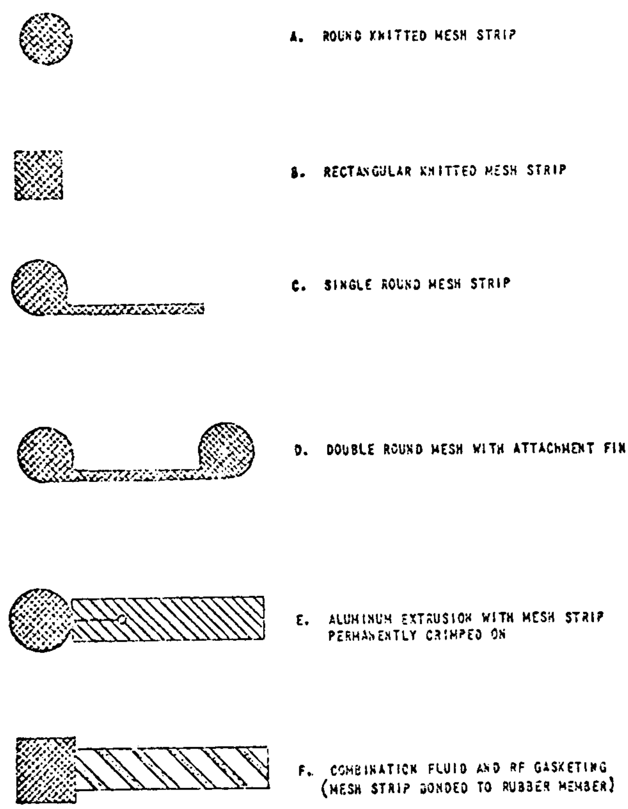

Fig. 4-23. Various Gasket Configurations

CHAPTER 5

TECHNIQUES USED TO EVALUATE WEAPON SYSTEMS

The problem of protecting a weapon system against radio frequency energy, lightning, and static electricity is complex. Even if the designer knew how to design each circuit to make it secure it is unlikely that the final design could incorporate all of these ideas. There usually are compromises somewhere in the design because of weight, size, cost, or incompatibility with other circuits. Also, there will be changes that occur in the production of the system, small changes which the manufacturer does not realize will affect RF susceptibility. The result of the accumulation of changes is a final product that is not as RF-hardened as the designer originally envisioned.

The users of weapon systems are aware of this problem and have set up certain test facilities to help determine the susceptibility of these systems. Subsystems and materials can be evaluated before being assembled into the final system. Those that fail to meet specification should be modified and then retested. This procedure can be repeated until the subsystem or material is found acceptable. This chapter is devoted to briefly describing the systems that the Army has available for susceptibility testing. Several reports on weapon systems are listed in the Bibliography which the designer can consult for insight on how these tests are conducted.

5-1 RADIO FREQUENCY TEST PROGRAM

The evaluation of the radio frequency susceptibility of a weapon system can be treated in two ways: (1) testing of individual components and subsystems, and (2) evaluation of the complete system. There are several factors to be considered when determining whether a complete system should be evaluated rather than individual components or subsystems. Individual subsystems and components are smaller; therefore, they are simpler to handle than a complete system, failure is easier to pin-point since only one unit is involved, and the environment can usually be more accurately controlled on a small scale. Evaluating the complete system has an advantage in that the testing is being performed on the system as it is actually used. The next several paragraphs discuss why and how these tests are run.

5-1.1 RADIO FREQUENCY SUSCEPTIBILITY OF COMPONENTS

The parts of a weapon system that should be considered from a radio frequency hazard standpoint are the electroexplosive systems, electronic circuits or guidance subsystems, and the propulsion subsystem. The individual components of a subsystem respond differently to a given RF stimulus and, therefore, require different testing techniques. The test procedures which follow are developed to help obtain information on the RF susceptibility of these components.

5-1.1.1 Electroexplosive Systems

One of the components in the electroexplosive system that is usually considered susceptible to external energy is the electroexplosive device. Par. 4-3 presents a detailed discussion of electroexplosive devices, and lists those (Table 4-17) that have been evaluated for RF sensitivity. A portion of this chapter gives the designer a brief idea as to how these electroexplosive devices are evaluated.

The designer is usually supplied with data on the all-fire current and the no-fire current of the EED. If not, he should refer to the sources listed in par. 4-3.1.2. The all-fire current is used to establish the magnitude of current that must be supplied from the power source for reliable initiation of the EED. The no-fire current is that current which sets the safety level for the circuit.

To allow for system and measurement uncertainty, a value of 10 dB below the no-fire level is used. Under no conditions should currents greater than this no-fire level appear in the circuit prior to firing. If they do, the circuit cannot be considered safe. This type of reasoning is carried over into RF susceptibility except that power is used as the hazard criterion. Conversion to power is necessary since it is the only parameter that can be accurately measured from dc to 10 GHz. Voltage and current measurements are difficult and, in most situations, meaningless at high frequencies since the impedance at the point of measurement is usually unknown. A thermocouple used to sense the heat in a bridgewire is actually measuring power even though it is calibrated in terms of dc current.

An approximation of the EED's power sensitivity can be achieved by using the EED's dc bridgewire resistance R and its current I to compute power P from $P = I^2R$. Typical curves of EED's sensitivity to RF are shown in Figs. 4-59 and 4-60. In order to obtain the all-fire level and the no-fire level, the devices are usually evaluated using the Bruceton Technique (Ref. 1) or the Probit Technique (Ref. 2).

For the system designer the 0.1% firing level is the most important datum when considered from a hardening viewpoint. This 0.1% firing level designates where there is a 0.1% probability that a given EED will fire. The 0.1% power level sets the maximum amount of power that the circuit containing the EED can pick up without the EED being considered in a hazardous condition (Ref. 3). It must be remembered that this 0.1% level is obtained statistically and represents the possibility that one out of a thousand items will fire when exposed to this level. As mentioned previously, to permit a safety factor to be placed on this 0.1% level, it has become standard practice to designate the no-fire level as 10 dB below the 0.1% level.

The two test methods most commonly used for EED evaluations are the Bruceton and the Probit. Of these, the Bruceton is more widely used since it can usually be conducted with a smaller quantity of devices. However, in instances where confirmation of an estimated probability at one particular level is required, the Probit test is preferred.

5-1.1.1.1 Techniques

5-1.1.1.1.1 Bruceton Technique

The Bruceton type of statistical testing is an experimental procedure that established sensitivity characteristics of components. With this technique the length of time that the stimulus is applied to the component under test is fixed while the magnitude of the stimulus is either raised or lowered by a fixed increment before each individual test, depending upon whether the preceding observation produced a function or a nonfunction. As an example, suppose that the voltage breakdown level for a group of capacitors is being determined, the test procedure would consist of the following steps:

a. Choose a stimulus level h to which the first specimen will be exposed.

b. Choose a positive incremental difference d.

c. If the first specimen breaks down when exposed at h, the second specimen is exposed at the next lower level $h - d$. If the first specimen does not break down the second specimen is exposed at the next higher level $h + d$.

d. The test is continued for the desired number of specimens, the stimulus for each device being stepped down or up one level, according to whether the previous one did or did not break down. In this manner one obtains a sequence of functions *(X)* and nonfunctions (0) from which can be derived a mean (50%) level and standard deviation.

From a statistical analysis the prediction is obtained of the maximum voltage at which these capacitors should be rated. A sample Bruceton test form documenting the results of a test on an EED is shown in Fig. 5-1.

5-1.1.1.1.2 Probit Technique

A typical example of a Probit analysis follows. Consider the data on p. 5-5 obtained from evaluating EED's (or any other component) at several power levels where X represents initiation (function) and 0 a nonfire (nonfunction).

Plotting these data for percent firings versus power input and drawing a line through the points, the graph in Fig. 5-2 is obtained. Since the data points do not fall in a straight line, a judgment has to be made concerning where to draw the line. Values taken from this estimated line and the original test data can be entered into a set of equations that will generate a new line that will present the best mathematical fit for the experimental data. Once this second line is drawn, an estimate of any firing level can be made.

The Probit techique is ordinarily used where one's interest is in specific probability levels. By expending greater quantities of EED's at or near the level of interest the estimate of the level is improved. If, for example, the 90 percent probability level is accurately required, then the majority of the items would be tested around this level. By so doing, an accurate determination

* * * B R U C E T O N   A N A L Y S I S * * *

DATA,RF-500,P-P MODE,10CW,207D,32198-01,5/4/64

SER. NO.	RES. (OHMS)	FUNCT. TIMES. (mSEC)		LEVELS 1	2	3	4	5	6	7	8	9	10
401	.18	290.723	1				X						
402	.16	324.303	2			X							
403	.16	-	3		O								
404	.17	-	4			O							
405	.17	974.659	5				X						
406	.17	-	6			O							
407	.17	860.413	7				X						
408	.15	450.667	8			X							
409	.16	-	9		O								
410	.17	-	10			O							
411	.17	288.110	11				X						
412	.16	-	12			O							
413	.17	565.846	13				X						
414	.16	-	14			O							
415	.17	592.925	15				X						
416	.16	-	16			O							
417	.17	903.088	17				X						
418	.17	-	18			O							
419	.18	548.519	19				X						
420	.15	-	20			O							
421	.16	379.508	21				X						
422	.17	-	22			O							
423	.16	917.414	23				X						
424	.17	288.191	24			X							
425	.17	-	25		O								
426	.17	343.866	26			X							
427	.15	301.890	27		X								
428	.17	-	28	O									
429	.17	-	29		O								
430	.17	-	30			O							
431	.17	163.519	31				X						
432	.15	-	32			O							
433	.17	213.972	33				X						
434	.17	-	34			O							
435	.17	323.072	35				X						
436	.16	270.507	36			X							
441	.17	-	37		O								
442	.17	-	38			O							
443	.17	209.801	39				X						
444	.17	526.464	40			X							

LEVEL NO.	STIMULUS (WATTS)	1	I*I	NO	NX
1	.2936-00	0	0	1	0
2	.3295-00	1	1	5	1
3	.3697-00	2	4	13	6
4	.4148-00	3	9	0	14
5	.0000	4	16	0	0
6	.0000	5	25	0	0
7	.0000	6	36	0	0
8	.0000	7	49	0	0
9	.0000	8	64	0	0
10	.0000	9	81	0	0
				NO=19	NX=21

V A L I D I T Y   T E S T S

EQUALITY OF OCCURRENCE -OK

NO. OF RUNS- 29

LENGTH OF RUNS- 3

LOG OF FIRST LEVEL= -.53220 D= .050

AO= 31 AX= 55

BO= 57 BX= 151

MO= .33795 MX= .33107

MEANO= -.42562 MEANX= -.42625

SIGMO= .03054 SIGMX= .02989 SIGMA= .03020

S= .60394 G= 1.069 G*G= 1.142379

H= 1.236 H*H= 1.528367

CONFIDENCE INTERVAL= .04670

LOG OF 99.9%(95%CONF)= -.28594 99.9%(95%CONF)= .518 WATTS

LOG OF MEAN(50%)LEVEL= -.42595 MEAN(50%)= .375 WATTS

LOG OF 0.1%(95%CONF) = -.56596 0.1%(95%CONF)= .272 WATTS

Fig. 5-1. Bruceton Data Sheet

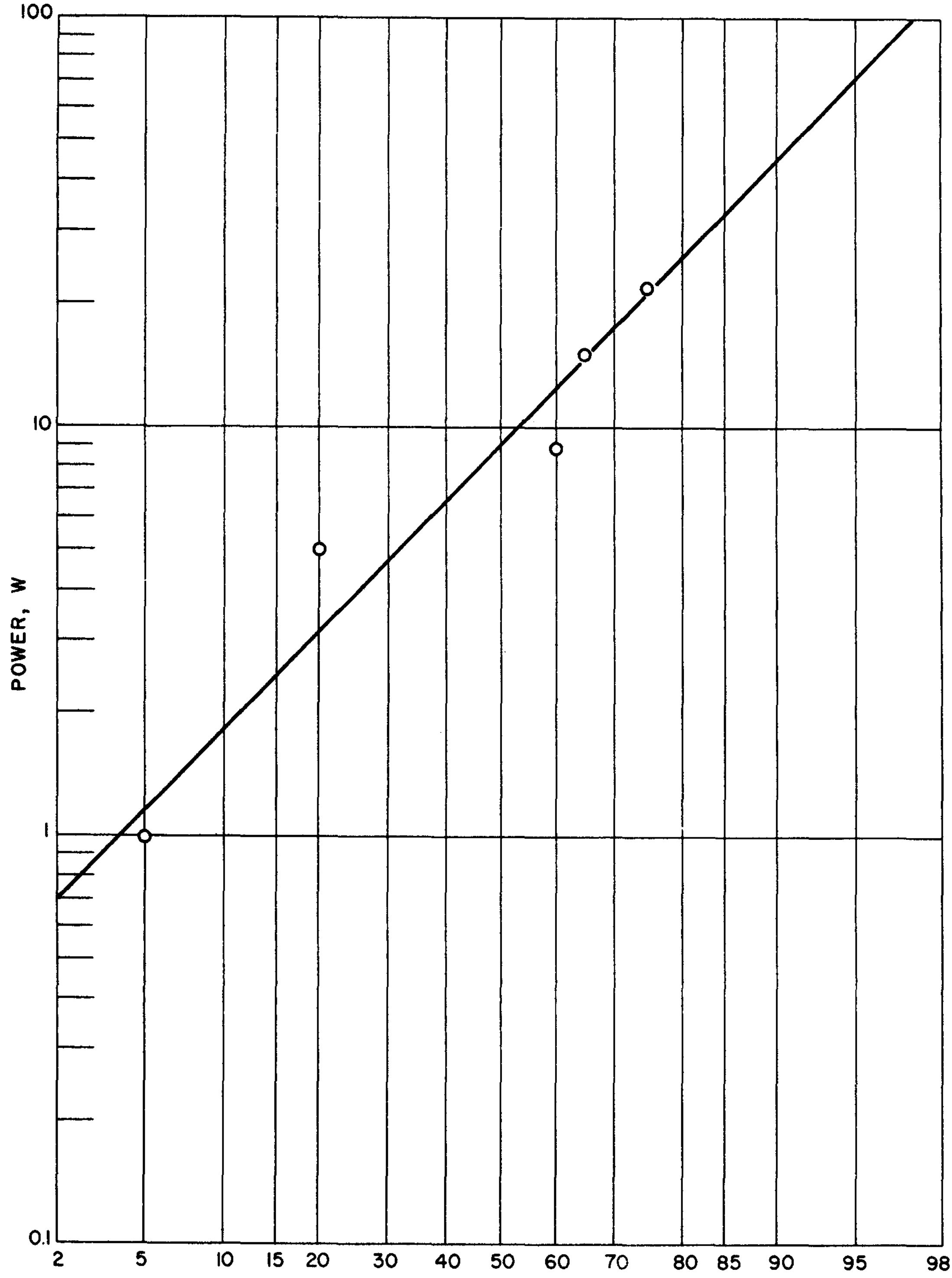

Fig. 5-2. Probit Estimate

POWER LEVEL, W	TEST RESULTS	NO. FIRED, %
1	00000000000000X00000	5
5	0X0000X000	20
9	X0X0X0XX0X	60
15	XXX0X0X0XX00XX00XXXX	65
22	X0XXXXXXX00XXX0X	75

would be made at this level, at the expense of information at other levels.

If tests are planned for extreme levels (99%, 1%) many samples will be required. The actual quantity required to insure that both fires and nonfires will be observed can be estimated by a binomial distribution (Ref. 4).

In its application to RF testing, the Probit method is infrequently used due to the limited amount of hardware usually available. There are, however, certain conditions under which it is desirable: (1) accurate estimate of a single point, and (2) recovery of data from a Bruceton test that was found to have errors in the assigned levels. These can be put in chart form and plotted as a Probit.

5-1.1.1.2 Evaluation Equipment

The basic equipment (Ref. 5) used in performing RF sensitivity tests is shown in Fig. 5-3. The RF generator supplies power to the transmission line while both the forward and the reflected power in the line are monitored. A switch permits the selection of either a standard termination (a fixed load which is capable of absorbing all of the incident power) or a termination consisting of a matching network followed by the EED in a specially designed mounting fixture. A chronograph determines functioning time. It is started by the application of the RF power and stopped by a signal from a flash detector. Other components include a variable attenuator to adjust the power delivered to the test specimen and the instrumentation needed for system calibration.

It is mandatory that the impedance of the specimen under test by transformed or matched to the 50-ohm impedance* of the system. This is done by a matching network consisting of variable reactive elements which may be either lumped or distributed, depending on the test frequency.

When the matching network is properly adjusted, there is no reflected power in the transmission line preceding the matching network (see par. 4-4 for a discussion of impedance matching). A null in the reflected power indicator shows that a match has been obtained. If the component losses in the matching network are small enough to be neglected, it can then be assumed that all of the incident power will be absorbed by the electroexplosive device.

While making the matching adjustments, very low power levels are used so as not to alter the characteristics of the device under test. A satisfactory match is assumed when the reflected power is less than 1% of the forward power. In setting the power to the full test level, the fixed load is used. The test exposure is started by diverting the power flow from the fixed load to the matched EED. The incident power level does not change during this operation since the input impedance of the fixed load is identical to that of the transmission line terminated by the matched EED, thereby leaving circuit conditions effectively changed.

Matching elements whose loss is negligible when correcting a 2-to-1 mismatch cannot be assumed lossless when the mismatch reaches a value of 10-to-1 or more, a situation which exists with most EED terminations. For this reason it is important in each situation to correct for these losses. The slotted line and variable probe indicated in Fig. 5-3 are used to obtain a correction factor that accounts for the loss in the matching network.

5-1.1.2 Electronic Circuits or Guidance Subsystems

The only test program that exists for electronic circuits is that contained in MIL-STD-461 and MIL-STD-462 (see Table 6-1) which are radio frequency interference specifications. Two portions of these

*There are two reasons for using 50 ohms as the standard: (1) most of the equipment on the market is 50 ohms, and (2) low impedance systems, such as 2-ohm strip line, are very lossy due to the use of a solid dielectric rather than air.

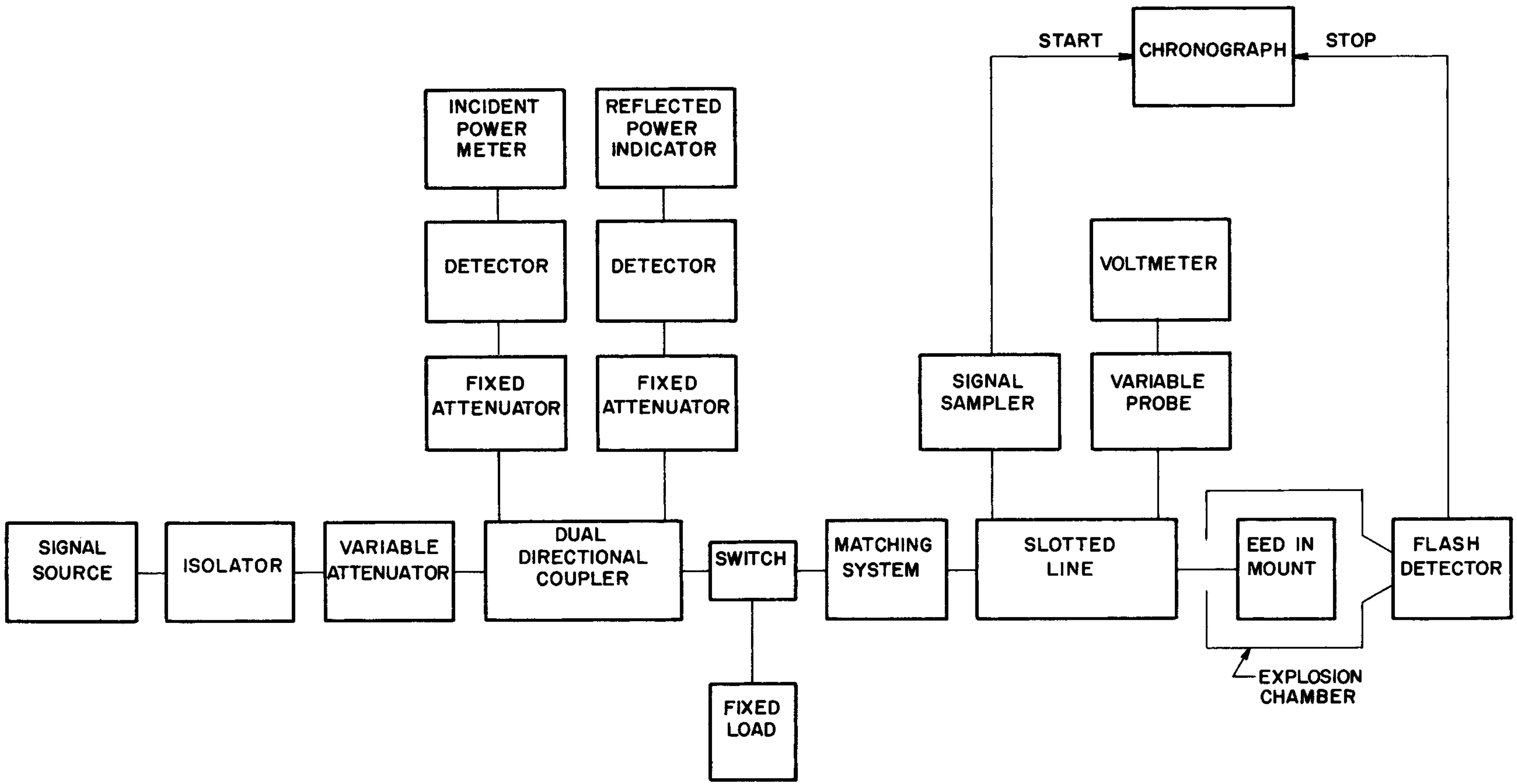

Fig. 5-3. Basic Equipment Used in Performing RF Sensitivity Tests of an EED

specifications are of interest for this work: (1) the radiated susceptibility, and (2) the conducted susceptibility. Under the first condition the circuit under consideration is irradiated by specified electromagnetic fields from 0.1 MHz to 10 GHz. To be considered not susceptible, the performance of the circuit must be unaffected by this exposure. The second test, conducted interference, consists of actually connecting the RF source to the power leads of the circuit. Once again the criterion for satisfactory operation is that the RF shall not affect the operation of the electronic circuit.

The field intensity specified by these two documents was not developed for the purpose of ascertaining the damage to a circuit under high intensity irradiation; the levels used are for interference malfunction determinations. Most subsystems such as receivers, amplifiers, servos, computers, etc., are required to meet MIL-STD-461 and MIL-STD-462; however, if the designer wishes to know how these electronic systems will function in an electromagnetic environment 100 times greater than that called for in these specifications, special tests will have to be specified. Tests of this type can be performed at certain Army facilities. These facilities and how the tests are performed are discussed in par. 5-1.2.2.

5-1.1.3 Propulsion Systems

The effect of radio frequency energy on propulsion systems appears to be negligible. No record of initiation or degradation has been reported since missile systems came into use. The one exception that should be noted is the situation where an EED is used to ignite the propulsion system. Under this condition the sensitivity level as defined in par. 5-1.1.1 should be used.

5-1.2 RADIO FREQUENCY SUSCEPTIBILITY OF A COMPLETE SYSTEM

With all of the complicating and generally uncontrollable factors, how then can one evaluate the potential RF hazard to a complete system? The answer at the present state-of-the-art is that it cannot be done with great precision for anything but a very specifically defined case; however, two methods are now in general use that can give a qualitative answer.

The first method is the application of analytical techniques to the system to determine the extent of RF hazard. This approach in its present form has two distinct advantages: (1) properly conducted the results are always on the safe side and, should it be demonstrated by this approach that a system is safe in a given field and at a specific frequency, its safety can practically be guaranteed; and (2) the analysis is reasonably inexpensive. The main expense comes from the fact that to perform the analysis properly the RF sensitivity of the device terminating the system must be determined. The exception occurs when the circuits are so well designed from an RF standpoint that it can be demonstrated analytically that protection levels are so large that the sensitivity of the terminating device is not a factor after installation in these circuits. The main objection to the present analytic method is that it can place unusually stringent restrictions on the circuits so that only the very well designed systems can be shown to be safe; in other words, the safety factor afforded thereby can be unreasonably large. This method is in wide use by the Air Force and was used extensively to evaluate ordnance circuits in both MINUTEMAN II (Ref. 6) and AGENA D (Ref. 7). The Army has used this approach on a limited scale; an example is the SPRINT program (Ref. 8).

The second method, stated briefly, is to irradiate directly the system in question with a variety of high-powered transmitters and to observe the RF levels that arrive at the component or subsystem under test. The method is appealing, although expensive, since it is a direct approach which appears to simulate the actual conditons that will occur. But, while such tests are often used and have a definite place in the scheme of things, there are disadvantages that should be noted. The chief weaknesses of the method include inadequacy of present RF detectors, inability to determine field strengths accurately, and the risk of assuming that tests on one or two systems can be extended to all such systems.

To minimize the effect of these various problems, irradiation tests are often conducted with an arbitrary safety factor added to the acceptable RF pickup at the detector (see par. 5-1.1.1). In addition, it should be recognized that the only positive result of a field irradiation test is to demonstrate that a hazard exists for the system being irradiated at certain frequencies, irradiation angles, polarizations, and orientations of the irradiating antenna. Specifically, a field irradiation test can never assure complete RF safety since only a finite number of frequencies, polarizations, etc., can be tested from the literally infinite number of situations that can develop in the actual use of the system. Part of this problem can be resolved by using swept frequencies. Properly conducted field tests, however, can give considerable assurance regarding RF safety.

5-1.2.1 Analytical Technique

The procedure for establishing the extent of the RF hazard to any system by means of the analytic method is:

a. The RF sensitivity of the particular device, subsystem, or system is determined over the entire frequency range of interest, for both continuous wave (CW) and pulsed RF signals and for all possible modes of damage such as through the regular leads or between the leads and the case or any other damage mode.

b. The details of the actual physical systems are established by using circuit and wiring diagrams; observation of the actual systems; observations and discussions of the handling, installation, and checkout procedures; and discussions with the engineers directly concerned. These details include such things as length of cables, locations of wiring breakouts, and separation between leads and the ground plane.

c. Mathematical models are constructed which closely resemble the actual wiring systems, and which can be handled with analytic techniques. These models are constructed for all phases of the problem; i.e., handling, check out, and installed. In the situation involving EED's, for example, pin-to-pin, pins-to-case, and bridgewire-to-bridgewire effects are also considered. All known parameters of the circuits are used such as the length of unshielded portions, and the physical shape. Whenever a parameter cannot be properly defined, a worst case assumption is made. For example, it is normally assumed that a given circuit is oriented with respect to the RF field for maximum pick-up of energy; that the entire circuit is in a simple plane; and that all impedances in the circuit are matched for optimum pick-up and transfer of energy.

d. The mathematical model is analyzed to establish the amount of RF energy that can be extracted from any incident RF field and subsequently transferred to the device under consideration. The analysis gives, for a particular circuit, a quantity known as "aperture" *a measure of ability to pick up energy.* The aperture as a function of frequency plot can be applied to any assumed field intensity.

e. For any assumed field intensity and frequency the amount of RF energy that could be delivered to the device being considered is obtained by the product of the incident power density and the aperture, and this value compared with its RF sensitivity. The degree of potential hazard is thereby established. Under the assumptions which are made, an indicated safe condition should be quite safe; an indicated hazardous condition may or may not be hazardous.

These data are usually presented graphically and in such a manner that as long as the same circuits and test items are employed, the analysis can be immediately applied to any change, present or future, in the incident field densities. Only those circuits which are completely different need be analyzed; for example, in the case of redundant circuits only one analysis need be conducted if the two circuits are similar.

This approach is often designated a worst case analysis, however, it should be noted that this is a mild misnomer. In actual fact, all of the known or reasonably obtained data bearing upon any circuit is used. For example, such details as actual sizes of loops, length of unshielded wire runs, separation distance of cable from frame, RF sensitivity and impedance of terminating device, quality of shielding material used, and attenuation provided by switches and arming devices used in the circuit are carefully determined. Actual values are used in the calculations wherever possible. On the other hand, those characteristics which could be variable from vehicle to vehicle or are very expensive to determine are assumed to be at their worst. For example, orientation of all circuits is assumed to be optimized in the incident field, impedances throughout the circuit are generally assumed to be matched in such a manner as to give maximum transfer of RF energy to the terminating device, RF pickup from all loops is assumed to be in phase, and missile skins (except under unusual circumstances) are assumed to offer no attenuation. Experience has shown this last assumption to be quite valid.

As a result, the analysis produces values of RF power delivered to the termination which are always on the conservative side, occasionally by rather large amounts. This leads to the statement made earlier–i.e., if under the worst case approach a system is found to be safe, it is most likely quite safe; if on the other hand a hazard is indicated, the system may still be safe.

Three additional points should be noted, however. First, experience has shown that if the weapon system is considered to be exposed to a wide frequency band there is a good probability that at some point in the frequency spectrum the worst case assumptions will come close to being satisfied, and the analysis and the real conditions will come close to coinciding. Second, attempts to assign probability values to the worst case assumptions so as to modify the worst case analysis are extremely difficult to accomplish in any meaningful manner. Even if sufficient data were obtained in one or two systems to permit assignment of such probabilities, the next system may be so different that practically all of the former data is not applicable. Third, systems carefully designed with the RF hazard problem in mind will generally be shown to be safe by even this worst case analysis. Only those circuits which have serious deficiencies in this respect tend to fail and these circuits should in general be corrected anyway.

5-1.2.1.1 Detailed Analysis Procedures

The purpose of the paragraphs which follow is to describe in detail the mathematical procedures necessary to conduct an RF analysis on a system.

Before proceeding, a few of the general considerations should be stated. The object of the analysis is to determine the maximum amount of power which can be delivered to any particular failure mode of the device under consideration. It is assumed that the incident RF field is essentially TEM; i.e., far field. Under these conditions the power density PD can be expressed as

$$PD = |\overline{PD}| = |\overline{E} \times \overline{H}| \frac{|\overline{E}|^2}{Z_o} = |\overline{H}|^2 Z_o \qquad (5\text{-}1)$$

where

PD = power density, W/m^2
$|\overline{PD}|$ = power density, absolute, W/m^2
$\overline{E}$ = electric field, V/m
$\overline{H}$ = magnetic field, A/m
Z_o = impedance of free space, 377 Ω.

The bars above the letters indicate vector notation.

With an incident TEM field, the basic antenna formulas can be applied and the hazard expressed in terms of the effective aperture Ae which is defined by

$$Ae = \frac{W}{PD}, \text{ m}^2 \qquad (5\text{-}2)$$

where

Ae = effective aperture, m^2
PD = power density, W/m^2
W = power dissipated in the antenna load, W

This concept of aperture is used in all the analyses which follow.

A general equation (Ref. 9) for expressing the effective aperture is

$$Ae = \frac{V^2 R_T}{\left[PD \quad (R_R + R_A + R_T)^2 + (X_A + X_T)^2\right]} \qquad (5\text{-}3)$$

where

V = total voltage induced in the antenna, V
R_R = radiation resistance, Ω
R_A = loss resistance of the antenna, Ω
R_T = termination resistance, Ω
X_T = termination reactance, Ω
X_A = antenna reactance, Ω

This basic equation is used to formulate many of the analyses.

In an actual computation the effective aperture must be calculated for each frequency of interest using the applicable equations. If the product of the effective aperture and incident power density at any given frequency is now formed, the result is the actual RF power delivered to the load under the assumed conditions. This value can then be compared with the sensitivity of the terminating device at that frequency to establish the possibility of RF susceptibility.

It is important to restate that the most important and necessary part of the analysis is to properly characterize the antennas represented. Experience has shown that the majority of present weapon system circuits fall into one of two categories. The first of these is the circuit which contains breakout of the shields going to circuit boards, through bulkhead connectors, or to other circuits. Most of these breakouts can be characterized as loops of varying dimensions. The second type is the circuit which is completely shielded from end to end and through 360° i.e., circumferentially. The paragraphs which follow will treat these two possibilities.

5-1.2.1.2 Circuits With Shielding Gaps

Let us consider an ordnance circuit of a typical weapon system. Many EED firing systems use shielded cables between the S&A device and the EED, or if no S&A unit is used, between the timers or firing switches and the EED. For such circuits the first assumption used in arriving at the antenna models to be used is that the power coupled to the EED firing mode impedances through the braided shield of the cables is negligible in relation to that coupled to these impedances by the nonshielded portions of the wiring. In consequence, the models chosen represent the physical characteristics of the gaps or breaks in the shielding. Fig. 5-4 diagrams a typical break or gap in a shielded firing lead, and Fig. 5-5 diagrams the equivalent antenna model used for this gap. The dimensions given are representative of commonly used separation switches, i.e., switches that isolate EED's from firing units.

The impedances Z_{s1} and Z_{s2} are considered to be completely unknown while Z_{pp} and Z_{pc} represent the firing mode impedances (pin-to-pin impedance Z_{pp} and pins-to-case impedance Z_{pc}) of the EED transformed along the connecting lines to the separation switch. The models for pin-to-pin and pins-to-case pickup are thus seen to be, for the lower frequencies at least, small loops loaded with the indicated impedance. Further, assume that the transmission lines formed by the shielded cables that connect the gaps and the EED are lossless. This is to be expected since these cables are constructed of good conductors and good insulators, and the gap length will be small.

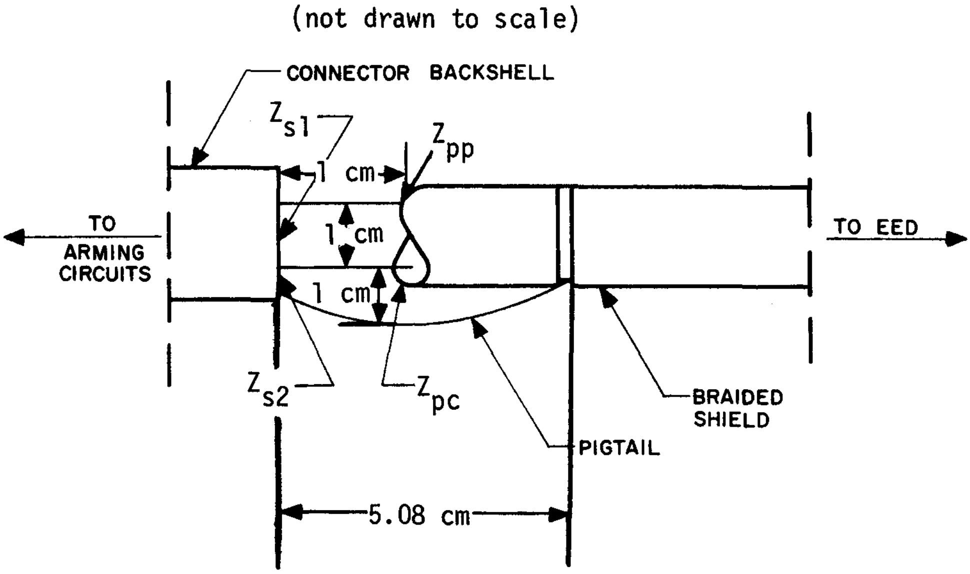

Fig. 5-4. A Typical Shielding Gap Configuration

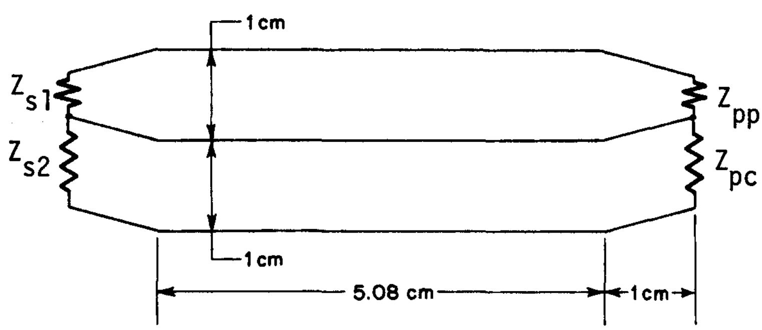

Fig. 5-5. Basic Antenna Model for a Shielding Gap

Once the loop has been reduced to its diagrammatic representation as shown in Fig. 5-5, the aperture for this loop can be calculated from the same equations as developed before. For wavelengths up to twice the perimeter of the loop, Eq. 5-4 applies. For shorter wavelengths, Eq. 5-5 applies.

$$Ae = \frac{4.67 \times 10^4 \, (Ar)^2}{\pi \, \lambda^2 \, R_T} \tag{5-4}$$

$$Aem = \frac{D\lambda^2}{4\pi} \tag{5-5}$$

where

Ae = effective aperture, m^2
Aem = maximum aperture, m^2
Ar = area of loop, m^2
R_T = termination resistance, ohm
D = directivity (ratio of maximum radiation intensity to average radiation intensity), dimensionless
λ = wavelength, m

These methods predict the maximum possible aperture of a single loop across the frequency range of interest. If more than one loop exists in the same firing

circuit the composite aperture of the combined loops is obtained, at all frequencies such that $2\ell < \lambda$, from

$$Aec = \frac{4.67 \times 10^4}{\pi \lambda^2 R_T} (Ar_1 + Ar_2 + Ar_3 + \ldots + Ar_m + \ldots + Ar_n)^2 \quad (5\text{-}6)$$

where Aec is the composite effective aperture of n loops and Ar_m is the *area* of the mth loop. This result reflects the fact that the methods employed in this frequency range are based on a maximum voltage and, since the voltage contributions of the individual loops could add in phase, they must be considered as a worst case possibility. In fact, at the lower frequencies where the wavelengths could be considerably longer than the circuit considered, this is a distinct possibility.

At the higher frequencies such that $2\ell \geq \lambda$ a similar procedure must be used; here the composite aperture is calculated from

$$Aec = \left[\sqrt{Aem_1} + \sqrt{Aem_2} + \ldots + \sqrt{Aem_q} + \ldots + \sqrt{Aem_n}\right]^2 \quad (5\text{-}7)$$

where Aem_q is the maximum aperture of the qth gap and Aec is the composite aperture of n gaps.

Fig. 5-6 shows the pin-to-pin aperture computed by these methods for a small shielding gap in a 6.4-Ω (dc resistance) EED firing circuit. The geometry of the gap is shown on the figure.

5-1.2.1.3 Example of an Evaluation

Fig. 5-7 is a schematic drawing of a simple system configuration taken from a weapon system. Fig. 5-8 is an approximation of this configuration shown as a simple loop, and finally Fig. 5-9 shows the antenna configuration for analysis derived from the actual circuit. R_T is the dc resistance of the EED.

The antenna configuration is a single loop; therefore, Eq. 5-4 can be used to compute the aperture for all wave lengths up to $\lambda = 2$ times the perimeter of the loop, i.e., for all wave lengths up to 76 cm or a frequency of 395 MHz. Above this frequency Eq. 5-5 is used. For each frequency of interest, and sufficient frequencies should be chosen to define the curve, one must calculate an aperture using the appropriate equation. Fig. 5-10 is a plot of such calculations made for the circuit under consideration.

The final step consists of using this aperture versus frequency data to produce a plot of RF power received at the EED as a function of the RF field incident on the system and to compare this RF pick-up with the RF sensitivity of the EED (refer to par. 4-3.1). Fig. 5-11 shows such a plot where the incident RF power density was assumed to be 2 W/m^2 up to 50 MHz and 100 W/m^2 above 50 MHz. The data for this plot were obtained by multiplying chosen points on the aperture curve of Fig. 5-10 by the assumed incident power density at the same point. Superimposed on the power pick-up curve of Fig. 5-11 is the RF sensitivity curve of the EED used in the installation. The conclusion one would draw from this plot is that, should this system be exposed to 100 W/m^2 fields across the frequency spectrum from 10 MHz to 10^5 MHz, safety could be guaranteed on the basis of the analysis only from 10 MHz to 80 MHz and from approximately 1600 MHz to 8500 MHz.

5-1.2.1.4 Completely Shielded Circuits

The situation where circuits are completely shielded with no gaps is desirable and it should be noted immediately that when this is done there is rarely any RF hazard problem involved with such circuits. However, it is sometimes necessary to demonstrate by analysis that such is the case. This situation is covered in detail in par. 4-1.

5-1.2.2 Irradiation Technique

The Army has two facilities that can be used to irradiate a complete weapon system. One of these facilities is located at White Sands Missile Range, New Mexico, and the other is located at Picatinny Arsenal, Dover, New Jersey. Both of these facilities can supply RF power from below 1 MHz to 10 GHz at very high power levels.

a. *White Sands RF Facilities*

Tests for determining the RF susceptibility of a complete weapon system can be conducted at the White Sands Missile Range. Fig. 5-12 shows a part of the SPRINT missile being irradiated by a low-frequency field at this facility. The frequency spectrum and the field intensity available at White Sands are documented in Fig. 5-13. These data were obtained early in 1968 and are constantly changing as new equipment is added.

b. *Picatinny Arsenal RF Facilities*

The RF hazard facility located at Picatinny Arsenal, Dover, New Jersey, is capable of generating the electromagnetic fields recorded in Fig. 5-14 (Ref. 10). A photograph of the facility looking toward the building that houses all of the power generators is shown in Fig.

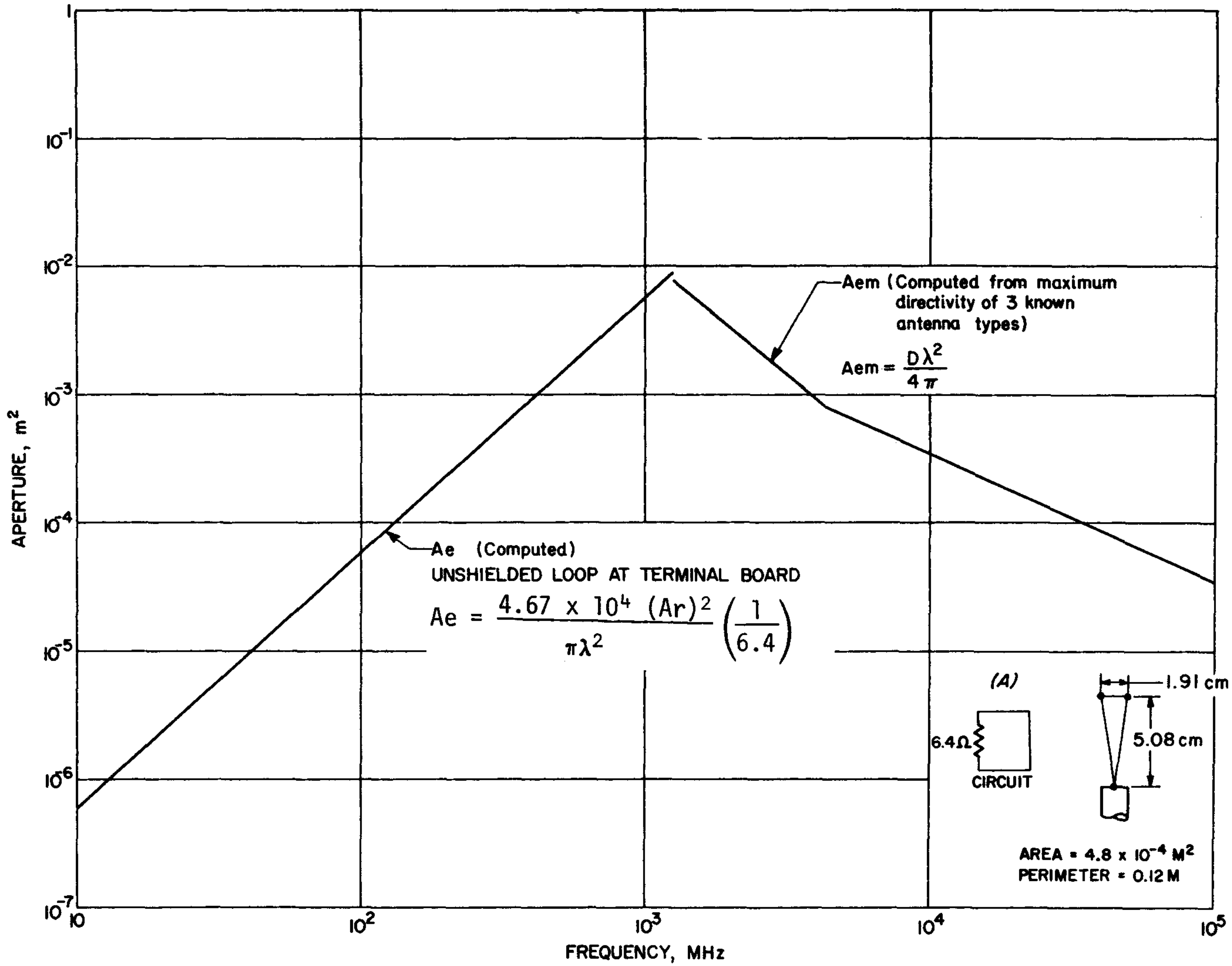

Fig. 5-6. Aperture of Loop as Shown in (A) at a Typical Terminal Board

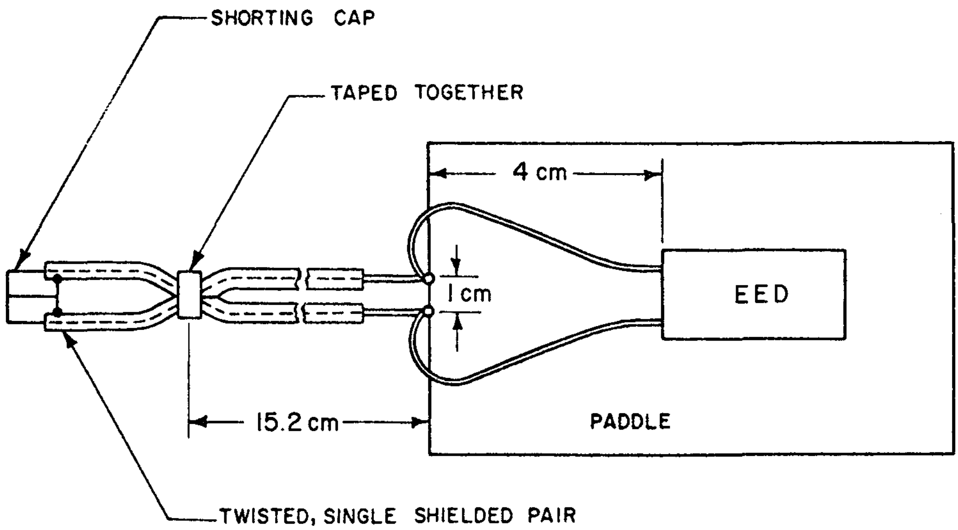

Fig. 5-7. Schematic Drawing of System To Be Analyzed

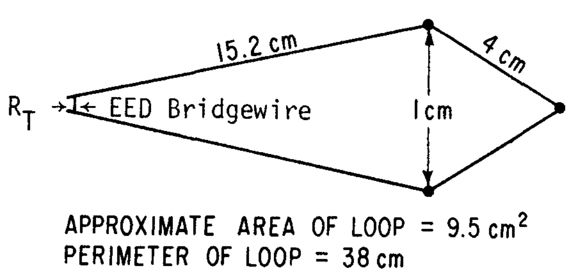

Fig. 5-8. Loop Approximation of System Shown in Fig. 5-7

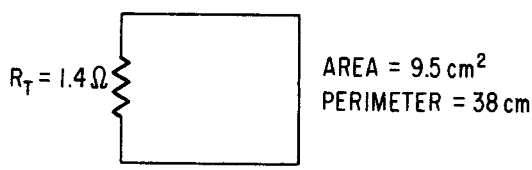

Fig. 5-9. Antenna Configuration for Evaluation Derived from Fig. 5-7

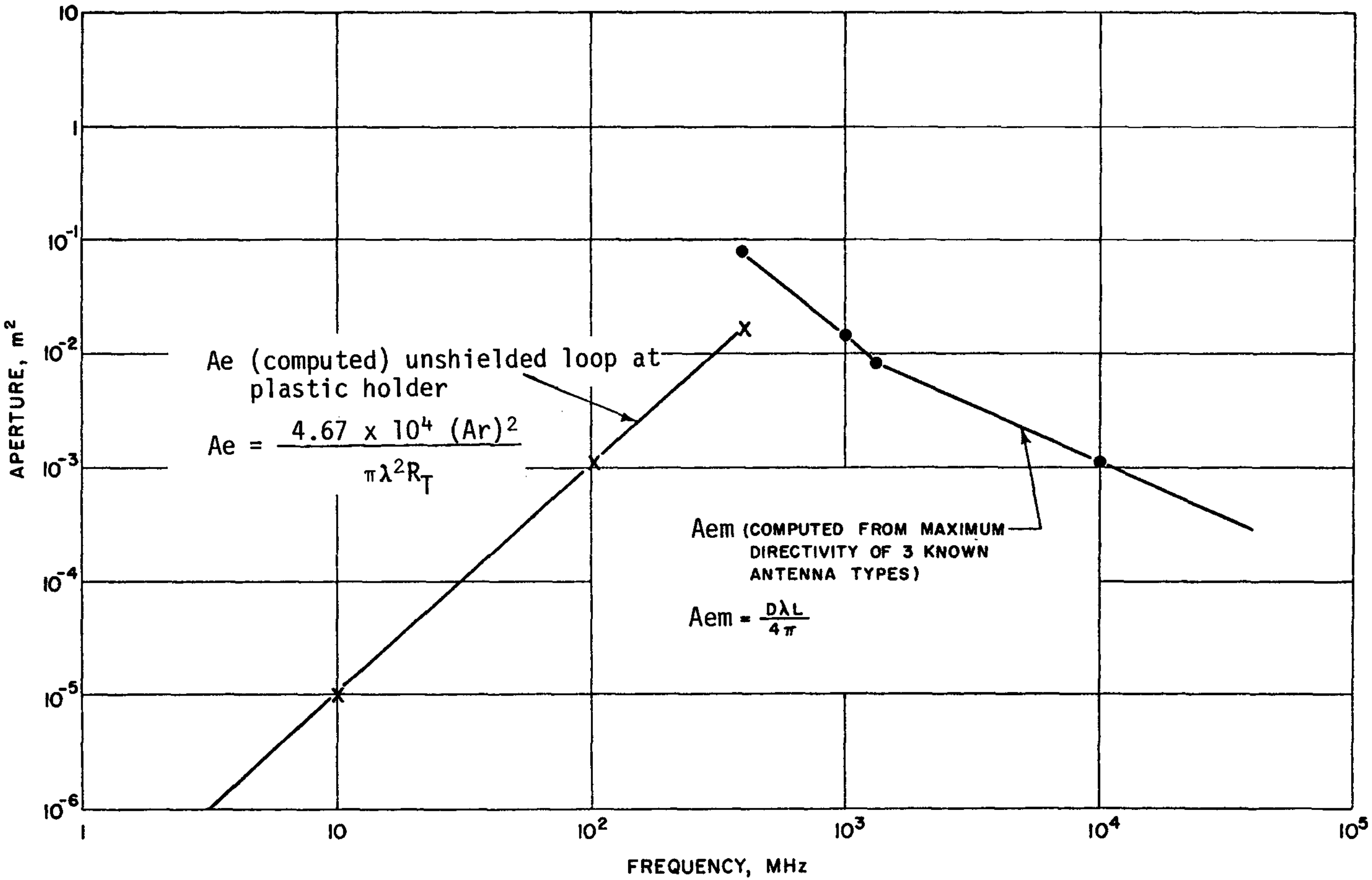

Fig. 5-10. Aperture of Loop Configuration at Paddle (Pin-to-pin Mode)

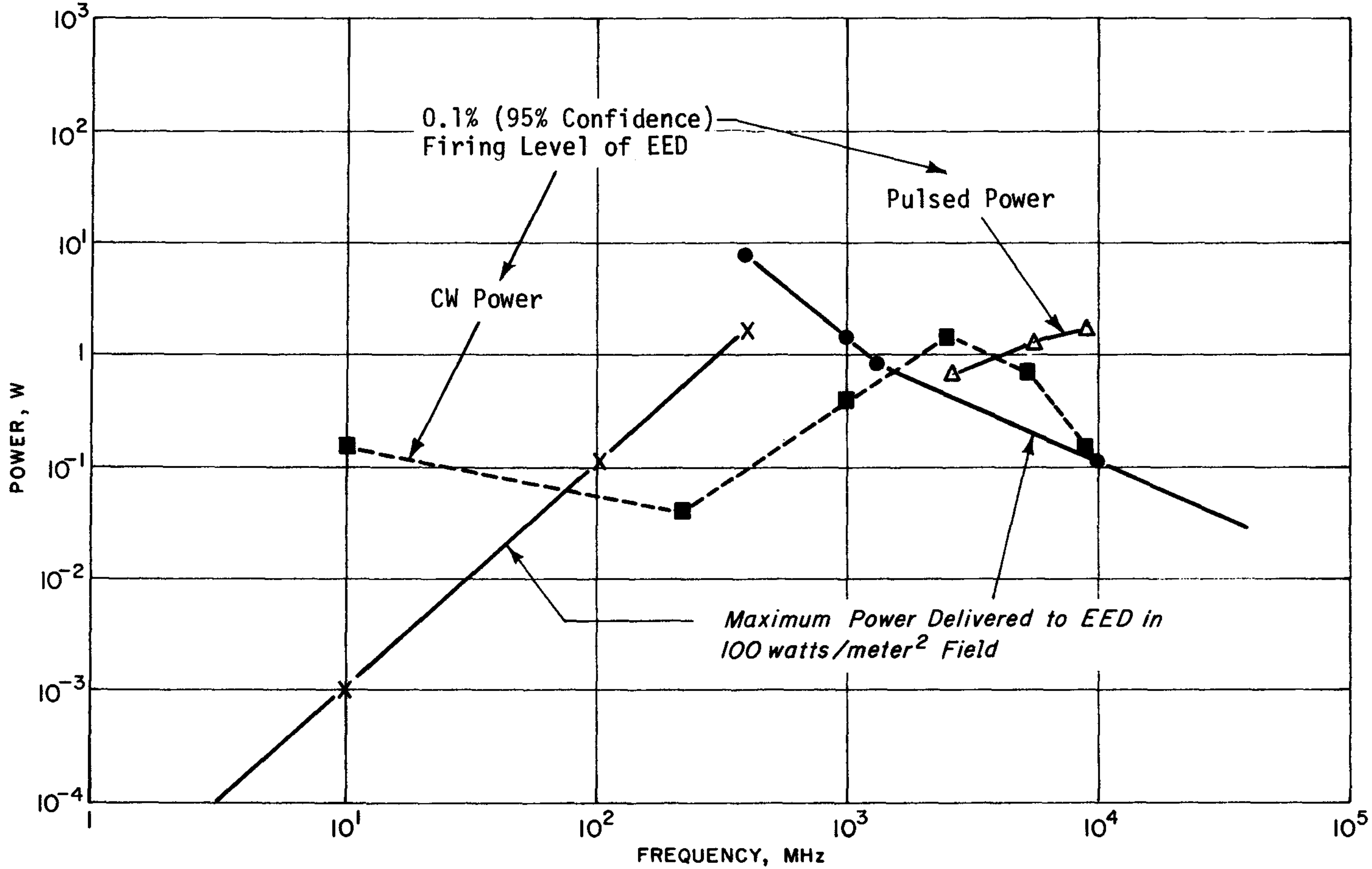

Fig. 5-11. Comparison of 0.1% Firing Level of the EED With Maximum Power Pick-up

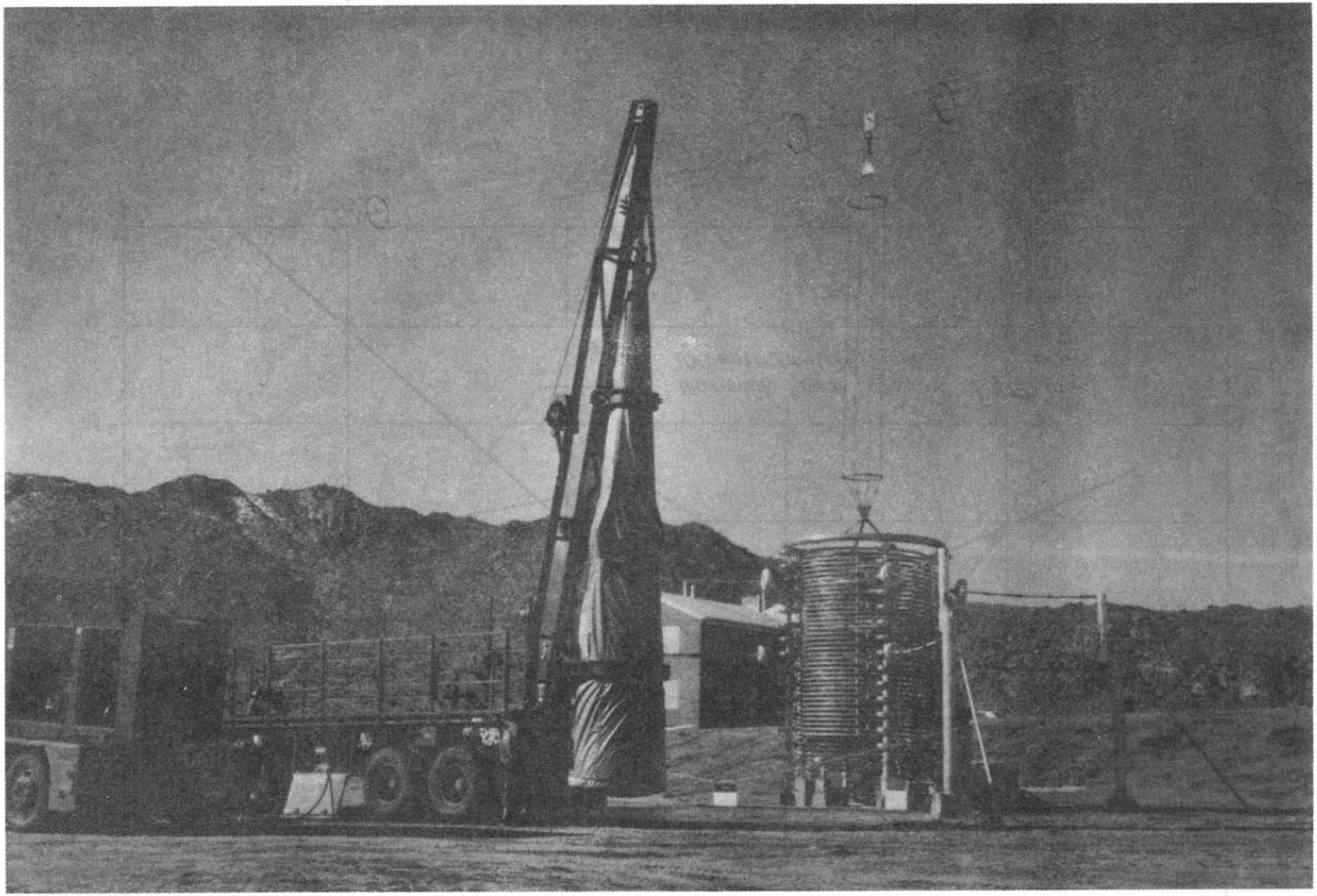

Fig. 5-12. SPRINT Missile Being Irradiated

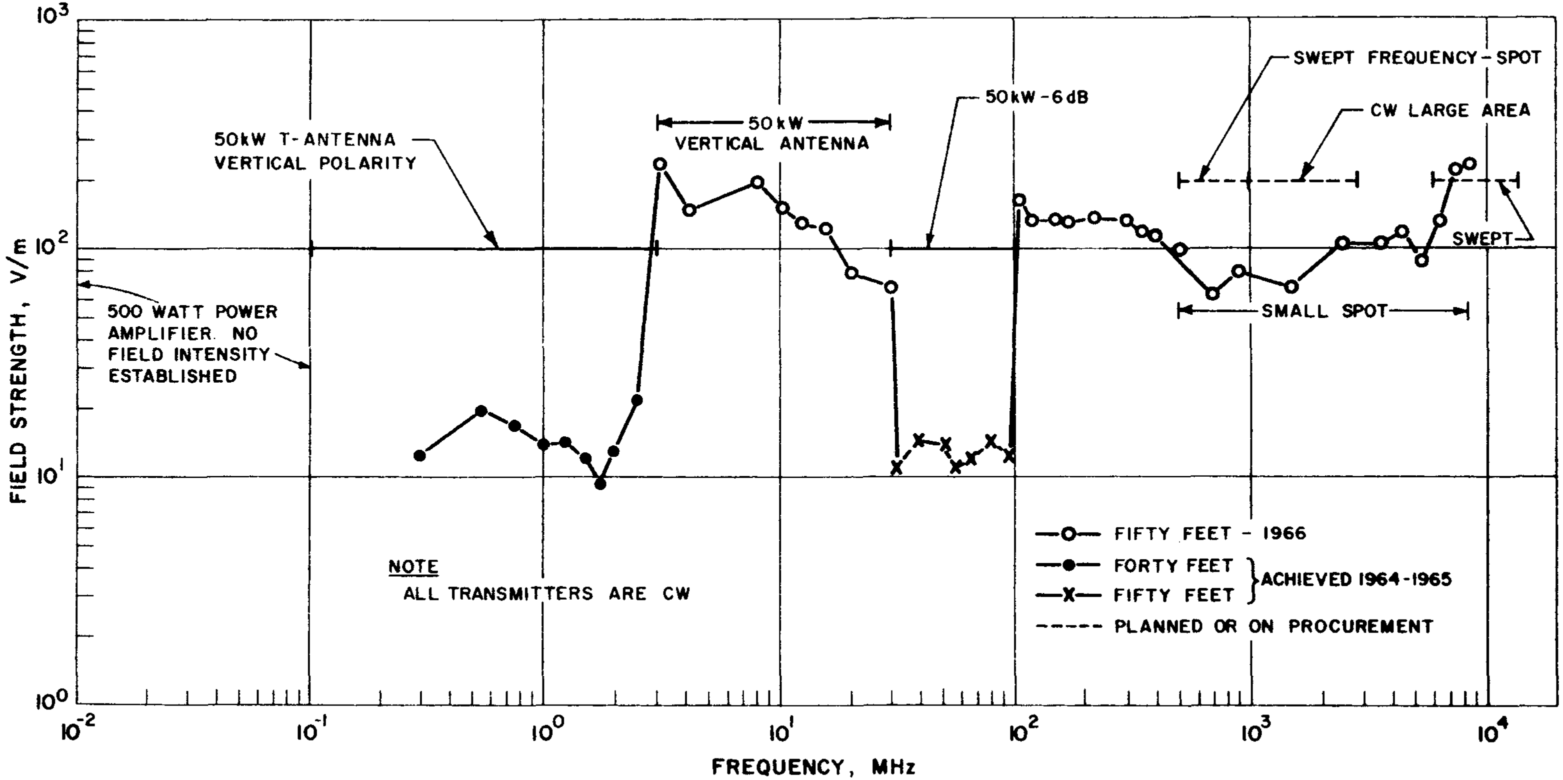

Fig. 5-13. Radiation Environment Available at White Sands Missile Range

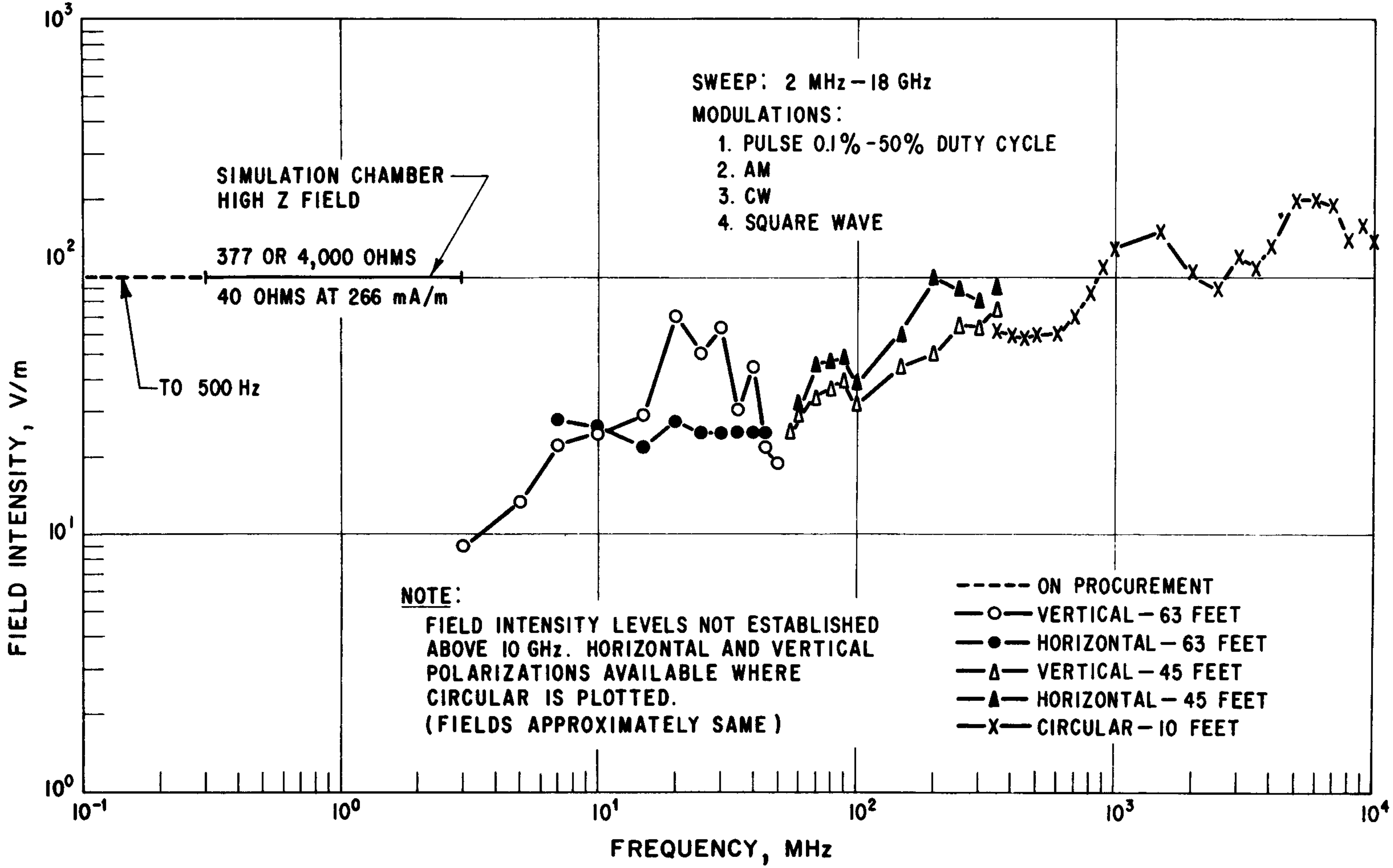

Fig. 5-14. Radiation Environment Available at Picatinny Arsenal

5-15. The facility includes a large ground plane in the center of the radiation pattern.

The dashed line in Fig. 5-14 represents the RF environment capability of the simulation chamber. The capability of the simulation chamber is as follows: A field intensity of 100 V/m is obtainable from 300 kHz to 3 MHz at a field impedance of either 377 ohms or 4,000 ohms; a 266 V/m field may also be obtained at a field impedance of 40 ohms. A transmitter is being procured to extend this simulation chamber capability down to 500 Hz. This chamber, shown in Fig. 5-16, is designed to produce a uniform field pattern so that a component or a system placed inside the chamber will be irradiated uniformly. The system is designed to accommodate weapon systems with major dimensions of 15 ft although items as large as 60 ft can be accommodated with certain limitations.

A list of reports generated by Picatinny Arsenal dealing with the RF susceptibility of weapon systems is contained in the Bibliography.

c. *Naval Weapons Laboratories RF Facilities*

The Navy has a facility located at the Naval Weapons Laboratories, Dahlgren, Va., for irradiating weapon systems with RF energy. This range may also be used by the Army for irradiation tests. A unique feature of this facility is the large metal ground plane (240 ft by 100 ft) located in the center of the radiation pattern (Ref. 11).

5-1.3 DETECTORS FOR RADIO FREQUENCY AND STRAY VOLTAGE HAZARD IDENTIFICATION

Irradiation tests performed on a weapon system can either damage or impair the later functioning of a particular component. If damage occurs, then the system is said to be vulnerable–at least to that frequency and field intensity that caused the damage; however, if no damage is noted, the question remains as to how close the test levels came to the damage point. To answer this question, components are instrumented to measure the amount of RF power being delivered to them when the system is irradiated. Tests are usually conducted at field intensities below that which damages the component or subsystem.

5-1.3.1 Electroexplosive Devices

5-1.3.1.1 Purpose of Detectors

In the study of the hazardous effects of RF energy on EED's, detectors capable of revealing quantitative information about the effects of an incident RF field have played an important role.

The most useful type of detector is the type that is used in a circuit in conjunction with or in place of an EED to determine the quantity of RF energy that would arrive at the device under a given set of RF input conditions. Such detectors are extremely valuable, both in the laboratory and the field. In the laboratory and field they can be substituted for live EED's for such tasks as determining the response of the test items at levels far below that which would normally cause any observable reaction in the live devices.

5-1.3.1.2 Types of Detectors

Several types of detectors have been or are being developed for use with simulated (inert) EED's. Most of these would be applicable to other types of electrical components as well. RF detectors may be broadly divided into two classes: (1) those that detect heat, and (2) those that detect voltage. The paragraphs which follow contain a general discussion of several types of detectors now in use or under consideration for use. Table 5-1 compares these detectors on the bases of sensitivity, pulse response, and instrumentation required.

a. *Heat-sensing Detectors:* Heat-sensing detectors are used primarily to detect the rise in temperature of a bridgewire caused by dissipation of RF energy in the bridgewire. The following are typical of the present state-of-the-art developments.

(1) The Clairex CL-404 detector is a cadmium sulfide cell, with a peak spectral response at 0.68 micron and extends beyond 1 micron into the infrared. As radiation from the bridgewire falls on the cell, the cell's resistance decreases. In most cases the cell can detect a bridgewire's infrared radiation which precedes visible glow. This detector, therefore, is useful for testing at the firing level of most initiators or at a few dB above the no-fire level. The ohmmeter scale of a multimeter may be used as an output meter for this Clairex cell.

(2) The Kodak Ektron N2 detector is a lead sulfide cell with a peak spectral response at 2 microns (Ref. 12) and extends to about 3.5 microns. These detectors are usually operated as matched pairs in a bridge circuit where one cell is exposed to ambient temperature and the radiating source. For optimum results a chopper should be used between the radiating source and the exposed detector. With the

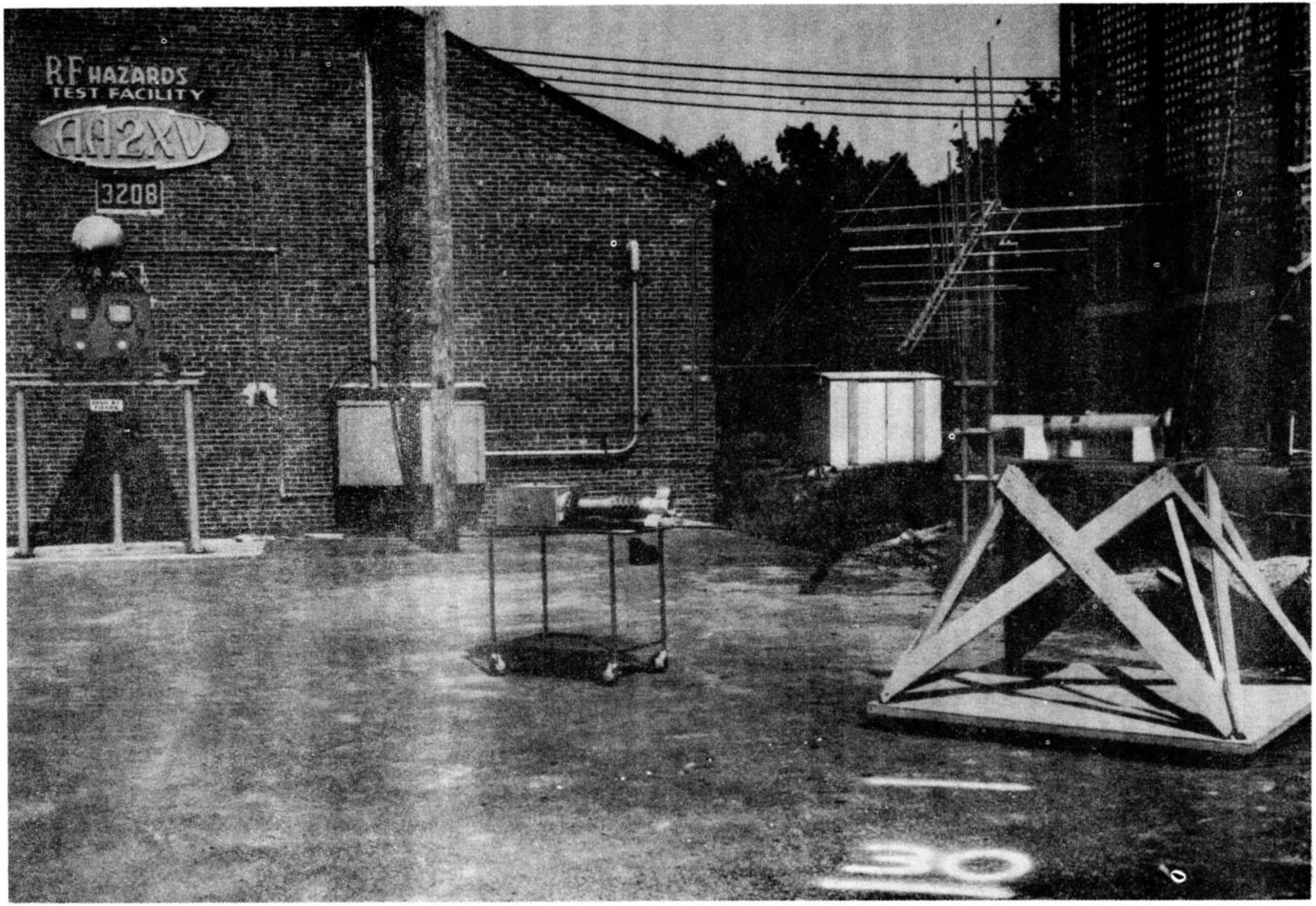

Fig. 5-15. DRAGON Missile System in Test

TABLE 5-1

COMPARISON OF DETECTORS

Type Detector	Maker of Basic Detector Element	Application to EED Developed By	Class	Power Sensitivity,(1) dB	Response (To Pulse)	Common Mode Rejection, dB	Minimum Auxiliary Instrumentation Required for Readout
CL-404 photoconductive cell	Clairex Corporation	Franklin Institute Research Labs.	Temperature Rise	+3	Poor	>60	Ohmmeter scale of multimeter
Ektron N-2 Cell	Eastman Kodak Co.	Franklin Institute Research Labs.	Temperature Rise	−8	Poor	>60	1000 Hz bridge circuit with amplifier and oscilloscope
Vacuum deposited thermocouple	NWL PA	Naval Weapons Lab., Picatinny Arsenal	Temperature Rise	−32	Poor	>60	Sensitive dc microvolt meter
NWL Colay Cell PEDRO	NWL	Naval Weapons Lab., Dahlgren, Va.	Temperature Rise	−28	Poor	>60	Specially developed instrumentation
VECO AX1364-E Thermistor	Victory Engineering	Applied to M3 squib in LITTLE JOHN at Redstone	Temperature Rise	−23	Poor	>60	dc bridge circuit and sensitive dc microvolt meter
Microminiature Thermocouple	Baldwin-Lima-Hamilton	Martin Co.	Temperature Rise	0	Poor	>60	Sensitive dc microvolt meter
1N830 diode (detector)	Sylvania	Applied to 207D and other EED's at Franklin Institute Research Labs.	Voltage	−40	Good(2)	20	Sensitive dc microvolt meter
Current Probe	Jansky & Baily		Current		Poor	>60	

(1)The number in this column represents the dB below the no-firing level that can be read.

(2)An oscilloscope can be used as the indicator.

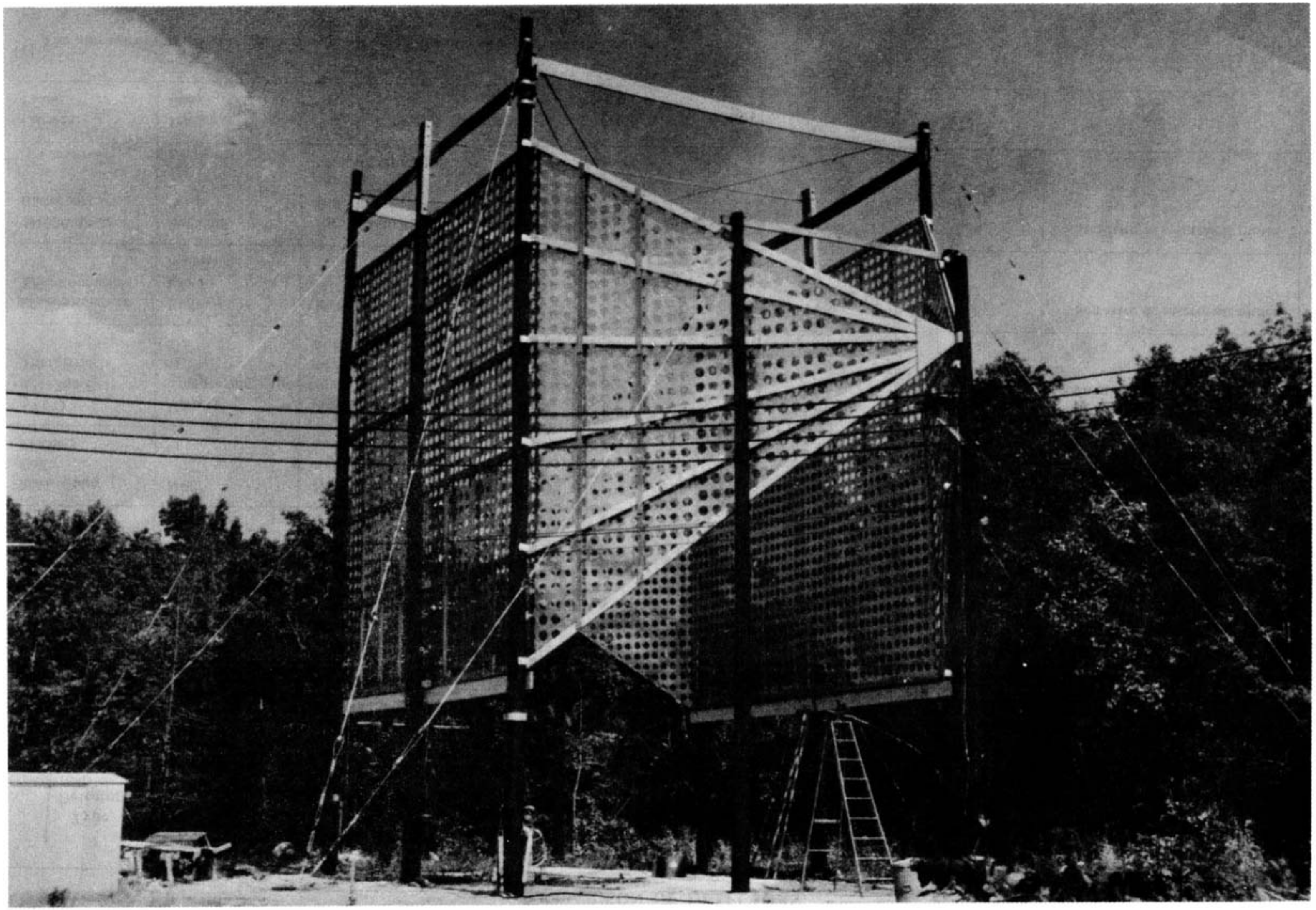

Fig. 5-16. Picatinny Arsenal RF Hazard Simulation Chamber, 300 kHz to 3 MHz, (To Be Extended Down to 10 kHz) 100 V/m, 266 mA/m, 377 ohms, 4,000 ohms, or 40 ohms (Preliminary Checkout)

present system, bridgewire power levels 8 dB below the no-fire level of many conventional initiators can be measured.

(3) A thermocouple may be used to sense the temperature of a heated bridgewire. A vacuum-deposited thermocouple installed within 0.003 in. of the bridgewire was developed by the Naval Weapons Laboratory (Ref. 13). The output of the thermocouple is read on a sensitive recorder or microvoltmeter and has a threshold sensitivity of 50 μW. Tests at the Denver Research Institute indicated good correlation of dc heating with ac heating up to 3 GHz. These are difficult to use above 800 MHz, however, because RF coupling causes spurious signals in the thermocouple output circuit. A later version developed by Picatinny Arsenal, using tellurium-palladium, can measure as low as 12.5 μW dissipation. Tests have also been conducted using a microminiature thermocouple (Ref. 14). Fig. 5-17 shows a BLH Electronics Co. TCRC-ES-25 chromel-alumel microminiature thermocouple mounted above the bridgewire of an EED. These units are easy to assemble but lack the sensitivity of the vacuum deposited thermocouple.

(4) Thermistors–extremely small bead type–are now available. Such thermistors with a nominal resistance of 5,000 ohms exhibit a resistance change of approximately 70 ohms per °F of temperature excursion. If one of these thermistors is mounted above the bridgewire of an initiator, it is possible to detect a relatively small temperature rise in the bridgewire. The thermistors are normally used in matched pairs in a bridge circuit where the second thermistor compensates for changes in ambient temperature. Even with matched pairs, the drift problem associated with significant ambient temperature changes is of such magnitude as to render this technique impractical.

A thermistor-type squib hazard detector was adapted to the LITTLEJOHN missile system at the Propulsion Laboratory, U.S. Army Missile Command, Redstone Arsenal, Alabama (Ref. 15). This detector system had four thermistors as arms of a Wheatstone bridge. Two of the four thermistors were mounted above the bridgewire for increased sensitivity.

(5) The Golay Cell is another type of heat sensing device. A Golay Cell is a gas chamber where

NOTE:
ECCOBOND 56C USED AS A CONDUCTIVE BONDING MATERIAL AS NEEDED.

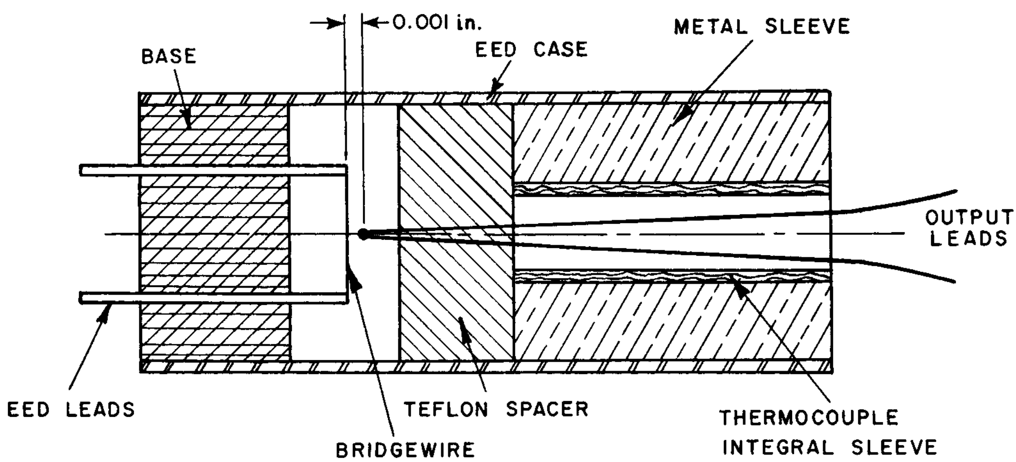

Fig. 5-17. EED Instrumented With a Microminiature Thermocouple

the pneumatic pressure in the chamber is increased when the gas is heated by the energy transferred from the bridgewire. An adaption of this principle was developed by the U.S. Naval Weapons Laboratories and incorporated in an inert MK1 Squib (Ref. 16). Heating of the bridgewire raises the chamber pressure and changes the curvature of a flexible mirrored diaphragm in the head of the squib. A remotely located light source and photocell detect the change in curvature of the diaphragm by means of fiber optics, thus avoiding influencing the RF signals being measured. This detector is in the experimental stage.

b. *Voltage-sensing Detectors:* The following instruments are typical of the state-of-the-art developments:

(1) The crystal diode detector is a typical example of the voltage-sensing type (Refs. 17, 18). Fig. 5-18 is a block diagram of one type of crystal diode detector and its associated instrumentation. The leads (points *A* and *B* in Fig. 5-18) are connected across the test device at the spot where RF voltage detection is desired. In most devices this has been directly across the bridgewire, but the detector can be mounted across other parts of the device, for example, between the pins and the case or bridgewire-to-bridgewire in dual bridge EED's. Properly designed, this detector has only minimal effects on the input impedance of the test item, exhibits fast response, and can be very sensitive; however, it is not linear with frequency. Calibration is normally direct, i.e., the calibration curve normally presents detector voltage as a function of input RF power to the test device. The common mode rejection is about 20 dB; therefore, 10% of the output is from the other mode. Table 5-1 compares characteristics of this detector with the heat-sensing types discussed previously. An indication of how small an EED can be–and still be instrumented–may be seen by the example in Fig. 5-19.

(2) The stray voltage detector (SVD) serves the frequent need for a one-shot type of detector which can be placed in the circuit being studied in place of the EED, and which will indicate if predetermined transient levels are exceeded at any time during the test or checkout phase. These SVD's, by closing a switch or triggering an alarm, can be made to indicate the time at which the predetermined level is exceeded.

An SVD that simulates a dual bridgewire EED is shown in Fig. 5-20. It comprises an EED which has a firing sensitivity selected to result in firing at the specified point of input energy, and whose output will be nondestructive. Circuits are built into the SVD so that it will simulate as closely as possible the device which it replaces. For the device shown in Fig. 5-20 it was desired that the SVD should fire on a stray current less than, but close to, the maximum no-fire level of the actual EED. Fig. 5-21 shows the response of the EED and the SVD (Ref. 19). SVD's of this lumped parameter type are not applicable to the detection of stray RF currents since the impedances at various frequencies will not resemble that of the EED.

5-1.3.2 Electronic Circuits

Development of detectors to instrument electronic components such as transistors, capacitors, inductors, resistors, etc., has not been accomplished. There is some work being done using current probes, but these are insensitive and are limited in their frequency response. At the present time, the only criteria are whether the components are damaged when irradiated or whether interference affects their performance in accordance with MIL-STD-461 and MIL-STD-462.

5-2 LIGHTNING

The facilities for evaluating a weapon system's vulnerability to lightning are not as extensive as those for RF irradiation. A portable 1.5×10^6 volt - 1.25×10^4 ampere Artificial Atmospheric Generator (Ref. 20) is available from the Army's Fort Monmouth Laboratory, Fort Monmouth, New Jersey.

Tests on components and subsystems (including warheads) can be conducted at the lightning Transient Research Institute, Minneapolis, Minn. Picatinny Arsenal also has provisions for making lightning tests on components and subsystems. The Picatinny Arsenal equipment illustrated in Fig. 5-22 is rated at 6×10^4 V and 4×10^4 A.

5-3 ELECTROMAGNETIC PULSE (EMP)

Measuring the effect of EMP under actual conditions is not practical since it would require a nuclear detonation above ground; therefore, several EMP simulation facilities have been constructed. One such installation

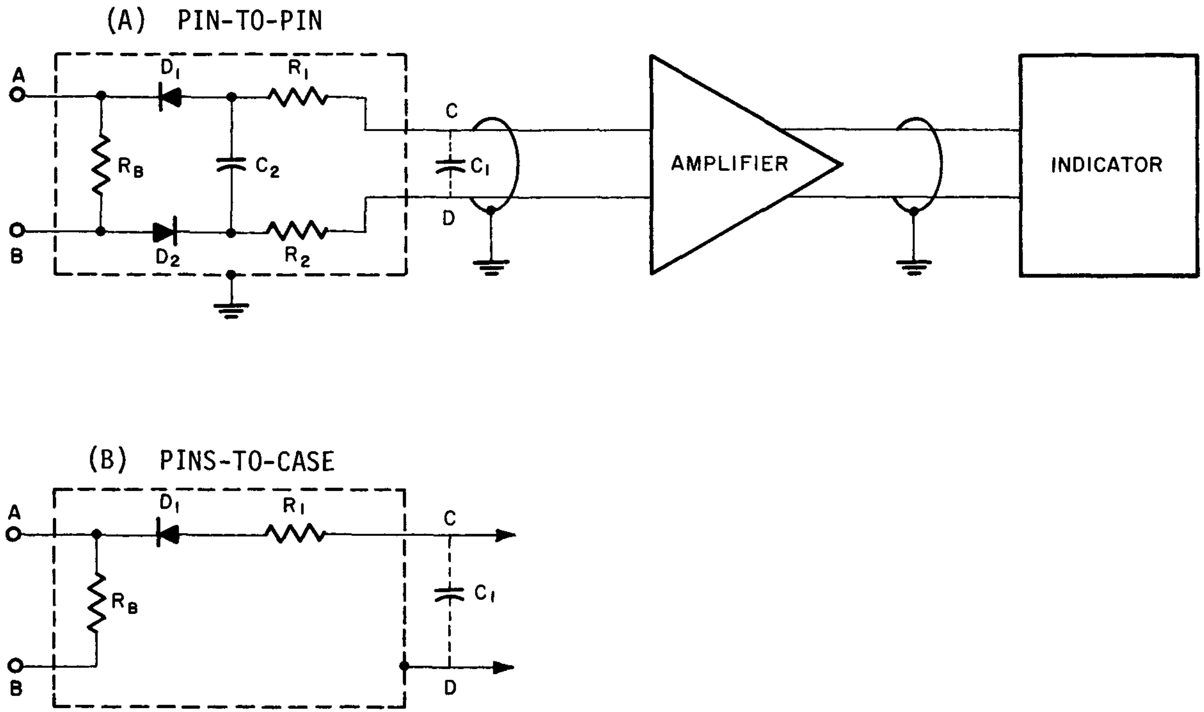

Fig. 5-18. Block Diagram of Crystal Diode Detector and Instrumentation

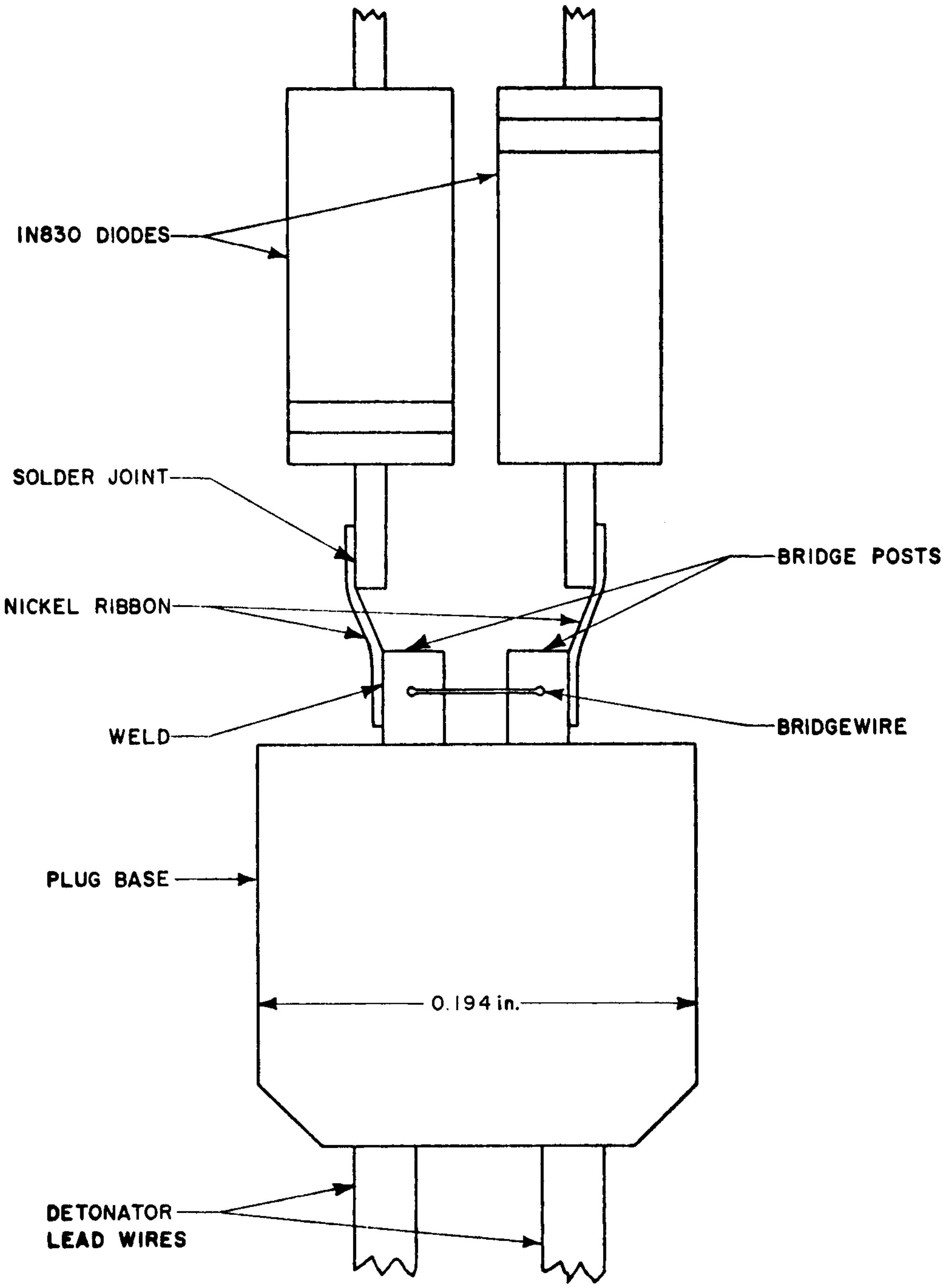

Fig. 5-19. Diode Detector Mounted on a Detonator Plug

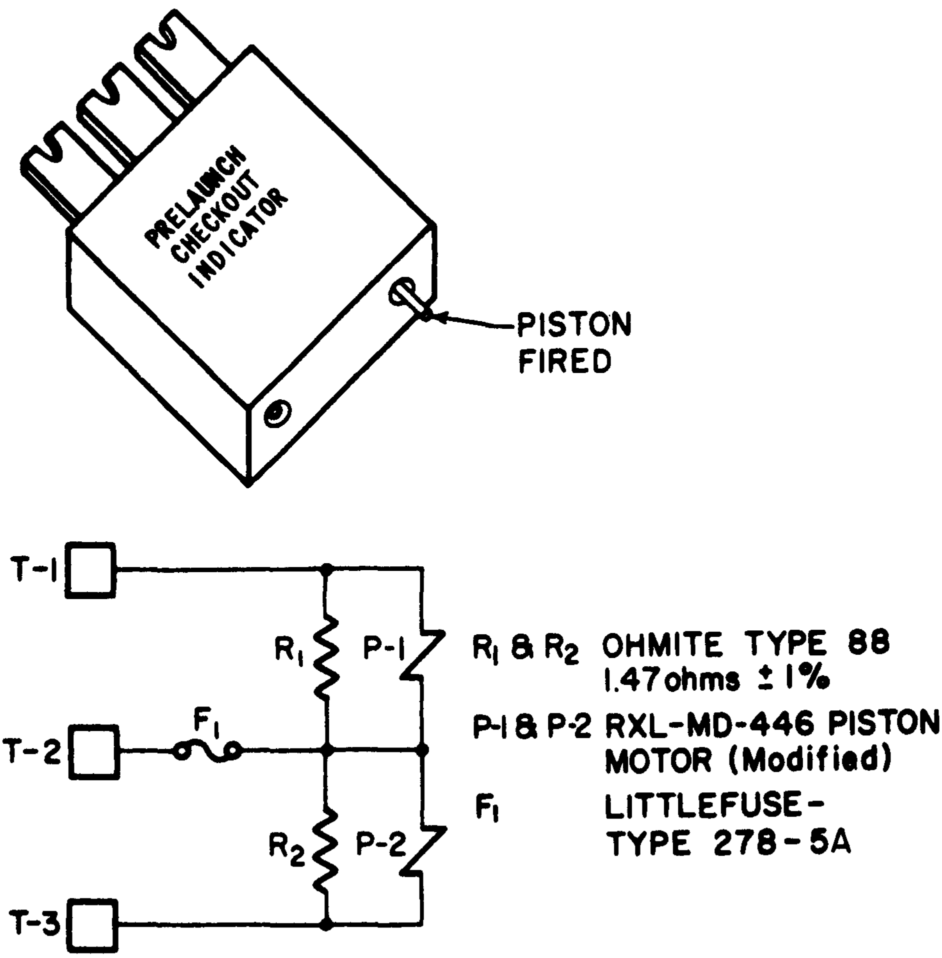

Fig. 5-20. Dual Bridgewire SVD

is the Facility for Research in Electromagnetic Effects (FREME) located at the U.S. Army Mobility Equipment Research and Development Center (USAMERDC), Ft. Belvoir, Virginia. Full-scale electromagnetic fields, indicative of the intermediate and late time characteristics of the environment created by a surface burst, are reliably simulated at this facility over the dimensions of all but the largest tactical Army systems. The FREME, like other EMP simulators, is capable of producing realistic environments over a portion of the time regime that is significant from an energy standpoint. It must be used in conjunction with other experimental techniques to cover the entire time regime of the EMP. The principal electromagnetic field source at the FREME consists of a conducting cylindrical coil, 51 ft in diameter and 60 ft in axial length, containing a set of thin conducting parallel plates electrically isolated from the conducting cylindrical skin. Horizontal magnetic fields and vertical electric fields are created independently within this coil by using five separate Marx generators, each capable of producing 1×10^6 V, as the drive system. The magnetic field is essentially uniform and unidirectional within the structure. The uniformity of the electric field depends upon temporary, voltage-divided guard rings, which are spaced between the conducting plates during particular experiments. An autonomous, transportable instrumentation system has been developed at USAMERDC for use with the FREME. The magnetic field is monitored with large, shielded, single-turn loops, differential

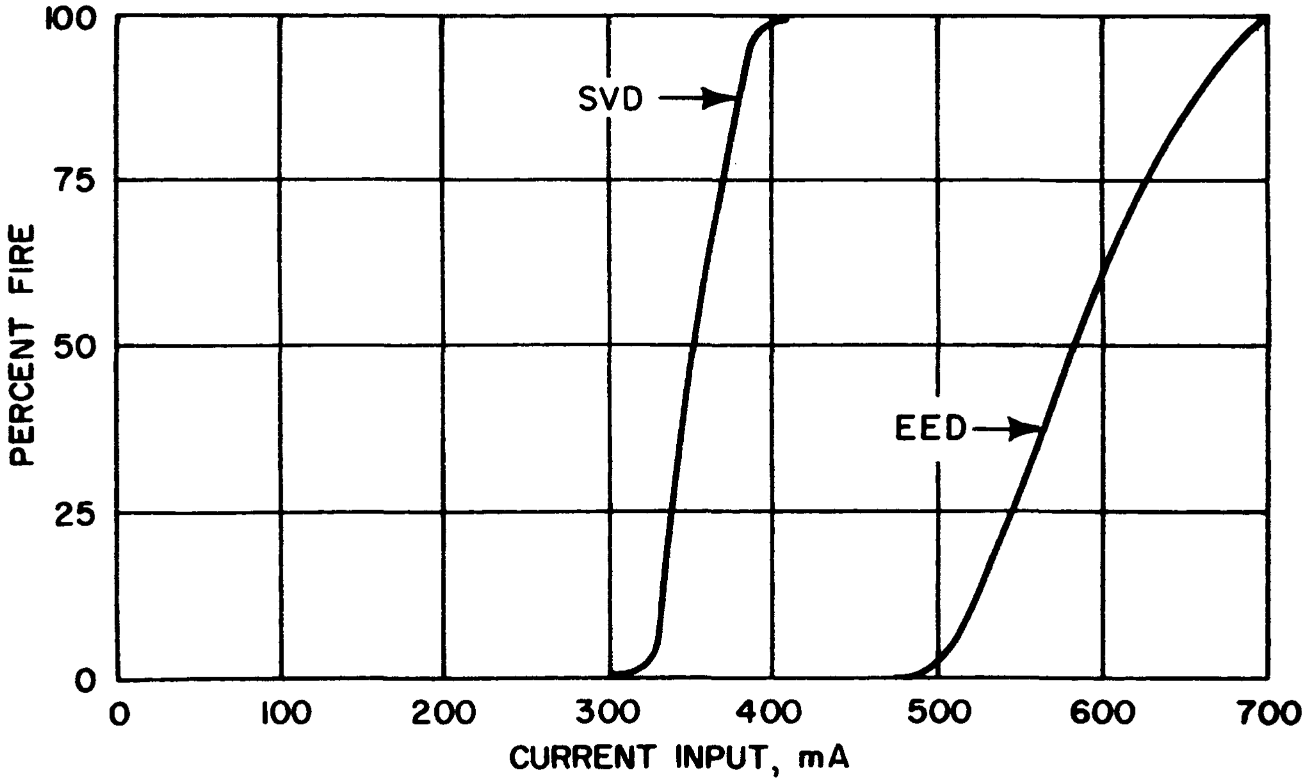

Fig. 5-21. Measured Response of SVD Compared to Replaced EED

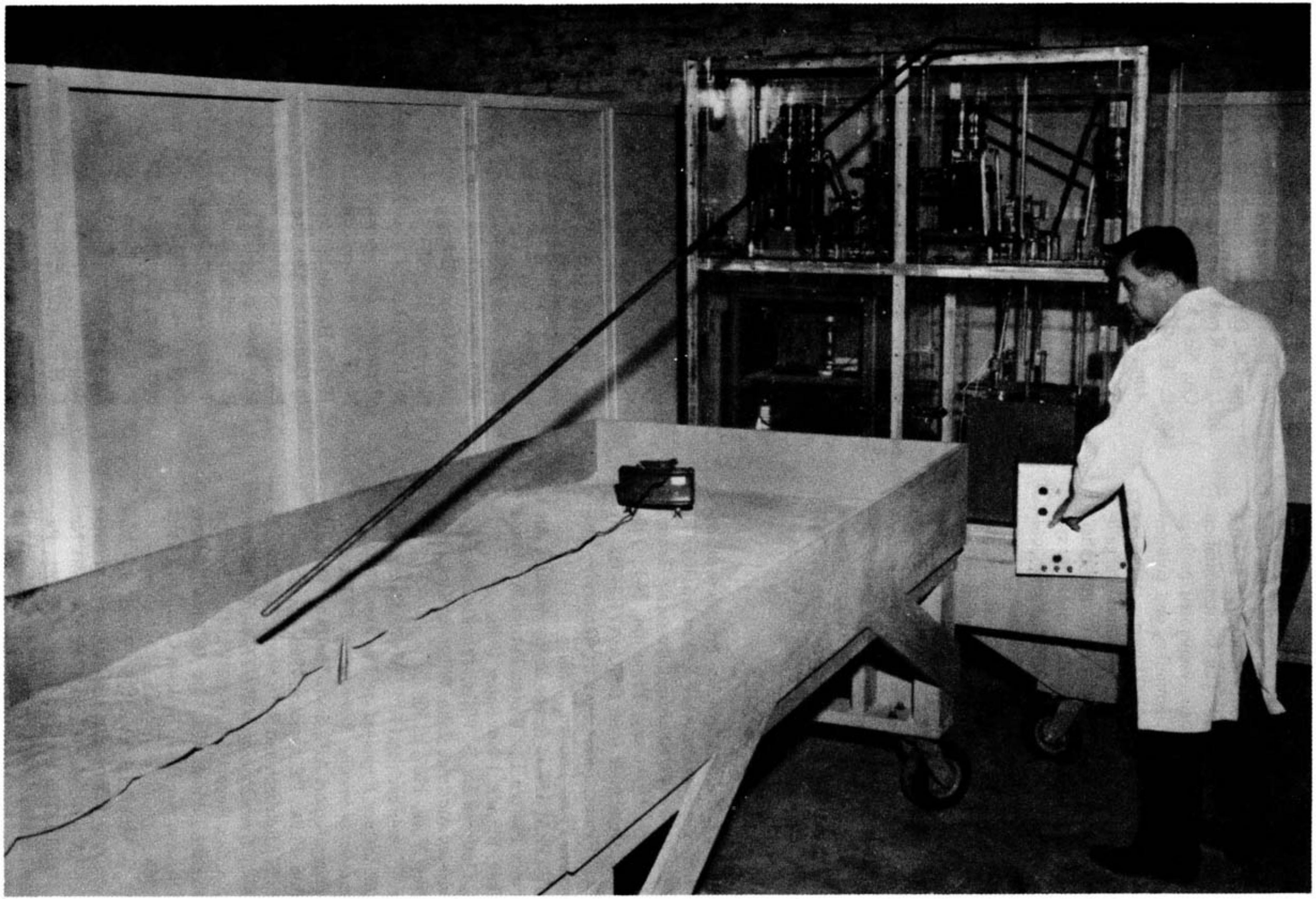

Fig. 5-22. Picatinny Arsenal Lightning Facility

cable, attenuators, and oscilloscopes. A 6-channel optical data link is used to measure the electric field, the voltages on components of equipment under study, and the currents within this equipment. This instrumentation system consists of a small battery-operated package containing a suitable sensor, amplifier, and gallium-arsenide diode to drive 12 ft of light pipe; a stationary light repeater containing photodiodes, amplifiers, gallium-arsenide diodes, and a lens; and photo multipliers with line drivers connecting to oscilloscopes. The system eliminates cables which cause field distortion, current injection into inclosures, and noise pickup. Portable, battery-operated oscilloscopes, with cameras, also may be used to gather data. A number of modifications are being considered to enhance the physical and electromagnetic characteristics of the FREME. These modifications include: increasing the energy storage capacity by 60 percent; decreasing the rise time of the electromagnetic environment; and developing alternate antenna configurations for producing meaningful EMP environments.

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CHAPTER 6

MILITARY SPECIFICATIONS FOR RADIO FREQUENCY INTERFERENCE/ELECTROMAGNETIC INTERFERENCE

6-1 INTRODUCTION

The first four chapters of this handbook are concerned with design techniques that will aid the designer in the development of a weapon system that is invulnerable to RF energy. There are, however, several Military Specifications that are concerned with the effects that an RFI/EMI environment will have on electrical and electronic equipment, and these specifications must be adhered to also. In the course of designing the system, the designer should be aware that the various pieces of equipment must perform without malfunction when exposed to a specified RF environment and must not itself radiate so as to influence other equipment.

6-2 APPLICABLE STANDARDS AND SPECIFICATIONS

To ascertain whether these requirements are being met, the Department of Defense has specified that certain tests be conducted. These tests are listed in Tables 6-1 and 6-2 along with a description of their scope and some brief comments. It should be noted that these Military Specifications were written for the control of RFI/EMI and not as a means of determining the vulnerability of a weapon system. The maximum field intensity for RFI/EMI tests is 10 V/m while vulnerability tests could require the use of several hundred V/m as a survivability standard. However, if the recommendations set forth in this handbook are followed, meeting the RFI/EMI specifications should not constitute a problem.

6-3 OTHER STANDARDS AND SPECIFICATIONS

There are other Military Specifications that deal indirectly with RFI/EMI and are encountered by the designer when he surveys the specifications. Many of these are not applicable to the immediate problem but this is difficult to ascertain by reading the titles of the documents. As a means of ready reference, these additional specifications are listed in Table 6-3.

6-4 COMPLIANCE WITH RFI/EMI SPECIFICATIONS

Electrical and electronic equipment used in military systems must meet certain RFI/EMI requirements in order to prevent degradation and interference. These requirements are called out in certain Military Specifications. Four of these specifications contain information on shielding, grounding, and circuit configurations. Many of the practices suggested in these documents are similar to those recommended in this handbook. To acquaint the designer with contents of these four documents, excerpts have been taken from them and placed in pars. 6-4.1 to 6-4.4. It should be noted that these are excerpts and do not constitute the total specifications. The purpose of this portion of the handbook is to present only the type of data that can be found in these type of documents. For complete information, both the total specification and the documents that they refer to should be read. When using these specifications, the designer should check to see if he has the latest issue. As an example, consider MIL-STD-449C listed in Table 6-1. The date on this document is 1 March 1965 and it supersedes MIL-STD-449B dated 20 July 1963. Up-to-date listing of the specifications can be found in *Department of Defense Index of Specifications and Standards.*

When the designer refers to the numerous RFI/EMI specifications, he is faced with the task of trying to decide which ones are applicable. The Department of

TABLE 6-1

APPLICABLE MILITARY STANDARDS

MIL-STD-	TITLE	Mandatory Use by	Scope	Comments
449C	RADIO FREQUENCY SPECTRUM CHARACTERISTICS, MEASUREMENT OF	Army, Navy, Air Force	This technical standard establishes uniform measurement techniques that are applicable to the determination of the spectral characteristics of radio-frequency transmitters and receivers. The ultimate goal is to ensure the compatibility of present and future systems.	Successful operation of most weapon systems depends upon the transfer of information to and from the system usually in the form of radio waves. Operation is degraded if other energy sources interfere with this flow of information; therefore, it is desirable to know the spectral characteristics of both the on-board and support receivers and transmitters. This standard establishes uniform measurement techniques of the spectral characteristics of the receivers and transmitters and gives forms for recording these data. This information is available to the designer and can be used to determine the characteristics of the receivers and transmitters that will be associated with the weapon system.
461	ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS, REQUIREMENTS FOR	Army, Navy, Air Force	This standard establishes the requirements for the measurement and determination of electromagnetic interference characteristics (emission and susceptibility) of equipment, systems, and subsystems.	The purposes of the standard are as follows: (a) To ensure that interference control design is incorporated into equipment, subsystems, and systems, and that applicable requirements are met. (b) To specify levels of electromagnetic interference emanation and interference susceptibility for equipment and subsystems that will enable compatible operation in a complex electromagnetic environment. The limits and referenced tests are established to increase the probability that operational systems or equipment will be compatible.

TABLE 6-1

APPLICABLE MILITARY STANDARDS (Cont.)

MIL-STD-	TITLE	Mandatory Use by	Scope	Comments
461 (con't)				This standard contains the requirements which are to be met when performing the tests specified for the electronic, electrical, or electromechanical equipment being purchased. The required tests referenced in this standard are found in MIL-STD-462.
462	ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS, MEASUREMENT OF	Army, Navy, Air Force	This standard establishes the accepted techniques used for the measurement and determination of electromagnetic interference characteristics (emission and susceptibility) of electrical, electronic and electromechanical equipment, subsystems, and systems in the frequency range of 20 Hz to 20 GHz (optional 40 GHz).	This standard takes the requirements set forth in MIL-STD-461 and presents a detailed discussion on how the tests are to be conducted.
463	ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS, DEFINITIONS AND SYSTEM-OF-UNITS	Army, Navy, Air Force	This standard establishes the system of units to be used.	The International System of Units, as adopted by the United States Bureau of Standards, is used in MIL-STD-461 and MIL-STD-462. MIL-STD-463 contains a complete description of these units.
826	ELECTROMAGNETIC INTERFERENCE TEST REQUIREMENTS AND TEST METHODS	Air Force	This standard establishes uniform test methods for testing equipment, systems, and subsystems to determine their electromagnetic interference and susceptibility characteristics.	Superseded by MIL-STD-461 and MIL-STD-462.

TABLE 6-1.

APPLICABLE MILITARY STANDARDS (Cont.)

MIL-STD-	TITLE	Mandatory Use by	Scope	Comments
833	MINIMIZATION OF HAZARDS OF ELECTROMAGNETIC RADIATION TO ELECTROEXPLOSIVE DEVICES	Air Force	This standard delineates criteria to be applied to the design of electroexplosive devices (EED's) and their application in systems. The purpose of this standard is to minimize the hazards of electromagnetic radiation to electro-explosive devices. The standard will apply to the design selection and application of electroexplosive devices and their firing circuits for all new development programs of systems that use electroexplosive devices.	This standard is used by the Air Force. It differs from the other MIL-STD's in that it deals with the hazard of electromagnetic energy to electroexplosive devices (EED's). EED's are required to meet one of the following standards: a. EED's will not fire as a result of the application of 1 watt of direct-current power for 5 minutes and also will not fire as a result of the application of 1 ampere of direct-current for 5 minutes. This requirement must be met without the use of external shunts. b. EED's with electroexplosive elements that do not meet the above 1-watt/1-ampere/5-minute standard will be designed so that the integral unit will survive in an electromagnetic field intensity of 100 watts per square meter. c. Recommended circuit configuration and shielding practices are included (see par. 6-4.4).

TABLE 6-2

APPLICABLE MILITARY SPECIFICATIONS

MIL-No.	TITLE	Mandatory Use by	Scope	Comments
A-3933B	ATTENUATORS, FIXED	Navy, Air Force, Army	This specification covers attenuators for use as attenuating elements in coaxial lines and waveguide. These attenuators are used for Armed Services application in the transmission lines of radar, radio and associated equipment.	This specification documents the various methods of measuring the worst case loss of an attenuator using matching systems.
B-5087B	BONDING, ELECTRICAL, AND LIGHTNING PROTECTION, FOR AEROSPACE SYSTEMS	Navy, Air Force	This specification covers the characteristics, application, and testing of electrical bonding for aerospace systems, as well as bonding for the installation and interconnection of electrical and electronic equipment therein, and lightning protection.	This specification is used by the Air Force and the Navy and deals with the bonding of metal-to-metal surfaces to provide protection against RF, lightning, and static electricity. Recommended procedures for preparing of the surface of the two metals to be joined is given. Methods of bonding are illustrated.
E-6051C	ELECTRICAL-ELECTRONIC SYSTEM COMPATIBILITY AND INTERFERENCE CONTROL REQUIREMENTS FOR AERONAUTICAL WEAPON SYSTEMS, ASSOCIATED SUBSYSTEMS AND AIRCRAFT	Army, Navy, Air Force	This specification outlines design requirements and tests necessary to control the electronic interference environment of weapon systems, associated electronic and electrical subsystems, and aircraft.	This specification can be considered as a guide for the contractor who is submitting equipment for approval. It tells what tests must be run but does not tell how to conduct the test. Test procedures are referred to MIL-I-6181D. Superseded by MIL-STD-461 and MIL-STD-462.

TABLE 6-2

APPLICABLE MILITARY SPECIFICATIONS (Cont.)

MIL-No.	TITLE	Mandatory Use by	Scope	Comments
E-55301	ELECTROMAGNETIC COMPATIBILITY	Army	This specification covers the electromagnetic interference reduction design requirements, emission and susceptibility limits, and test procedures for assuring the electromagnetic compatibility of all equipments and systems intended for use by the Department of the Army. It includes all types of items that are capable of generating or being adversely affected by electromagnetic interference.	Superseded by MIL-STD-461 and MIL-STD-462.
I-6181D	INTERFERENCE CONTROL REQUIREMENTS, AIRCRAFT EQUIPMENT	Army, Navy, Air Force	This specification covers design requirements, interference test procedures, and limits for electrical and electronic aeronautical equipment to be installed in or closely associated with aircraft.	Superseded by MIL-STD-461 and MIL-STD-462.
P-24014	PRECLUSION OF HAZARDS FROM ELECTROMAGNETIC RADIATION TO ORDNANCE, GENERAL REQUIREMENTS FOR	Navy	This specification establishes general requirements for weapon systems to preclude hazards from environmental electromagnetic fields in the frequency range of 10 Hz to 40 GHz. These requirements apply to all Navy weapon systems, including safety and emergency devices and other ancillary equipment, which contain electrically initiated, explosive or pyrotechnic components.	This specification is used by the Navy and deals with the hazards of electromagnetic energy to electroexplosive devices.

TABLE 6-3

OTHER RFI/EMI SPECIFICATIONS

MIL-No.	TITLE	Mandatory Use by	Scope
E-4957A	ENCLOSURE, ELECTROMAGNETIC-SHIELDING, DEMOUNTABLE, PREFABRICATED FOR ELECTRONICS TEST PURPOSES	Navy, Air Force	This specification covers shielding enclosures, (screen rooms) which are to provide specified frequency ranges for the purpose of test and alignment of electronics equipment and other related purposes.
E-8881A	ENCLOSURE, ELECTROMAGNETIC-SHIELDING DEMOUNTABLE, PREFABRICATED GENERAL SPECIFICATION FOR	Army, Navy, Air Force	This specification covers shielding enclosures which provide specified degrees of attenuation of electromagnetic fields for the purpose of test and alignment of electronic equipment.
E-18639A	ENCLOSURES, ELECTROMAGNETIC-SHIELDING, KNOCKDOWN DESIGN	Navy	This specification covers shielding enclosures which shall provide stated minimum degrees of attenuation to electromagnetic fields for the purpose of test alignment of electronic equipment and for other related purposes.
F-15733D	FILTERS, RADIO INTERFERENCE, GENERAL SPECIFICATION FOR	Army, Navy, Air Force	This specification covers the general requirements for current-carrying filters (alternating current (ac) and direct current (dc)), for use primarily in the reduction of broadband radio interference.
I-11683B	INTERFERENCE SUPPRESSION, RADIO, REQUIREMENTS FOR ENGINE GENERATORS AND MISCELLANEOUS ENGINES	Army	Superseded by MIL-STD-461 and MIL-STD-462.
I-25171	INTERFERENCE LIMITS AND TESTS FOR MODIFIED OR RECONDITIONED AIRCRAFT	Air Force	This specification covers interference limits applicable to aircraft being modified or reconditioned.
I-26600	INTERFERENCE CONTROL REQUIREMENTS, AERONAUTICAL EQUIPMENT	Air Force	Superseded by MIL-STD-461 and MIL-STD-462.

TABLE 6-3

OTHER RFI/EMI SPECIFICATIONS (Cont.)

MIL-No.	TITLE	Mandatory Use by	Scope
S-5786	SUPPRESSOR, ELECTRICAL NOISE, RADIO FREQUENCY	Air Force	This specification covers one type of radio frequency noise suppressor.
S-10379A	SUPPRESSION, RADIO INTERFERENCE GENERAL REQUIREMENTS FOR VEHICLES (AND VEHICULAR SUB-ASSEMBLIES)	Army, Navy, Air Force	Superseded by MIL-STD-461 and MIL-STD-462.
S-12348A	SUPPRESSION, RADIO INTERFERENCE GENERAL REQUIREMENTS FOR RAILWAY ROLLING STOCK, AND MAINTENANCE OF WAY EQUIPMENT	Army, Navy, Air Force	Superseded by MIL-STD-461 and MIL-STD-462.
S-13237A	SUPPRESSION, RADIO INTERFERENCE REQUIREMENTS FOR WATERCRAFT	Army	Superseded by MIL-STD-461 AND MIL-STD-462.
STD-220A	METHOD OF INSERTION-LOSS MEASUREMENT FOR RADIO-FREQUENCY FILTERS	Army, Navy, Air Force	This standard covers a method of measuring, in a 50-ohm system, the insertion loss of single and multiple-circuit radio-frequency filters at frequencies up to 1 GHz.
I-11748B	INTERFERENCE REDUCTION FOR ELECTRICAL AND ELECTRONIC EQUIPMENT	Army	Superseded by MIL-STD-461 and MIL-STD-462.
I-16165D	INTERFERENCE SHIELDING, ENGINE ELECTRICAL SYSTEMS	Navy	This specification covers requirements for interference shielding items and shielded harnesses for engine electrical systems aboard Naval ships, at advance bases, and in the vicinity of electronic installations. It includes the allowable interference limits for such items and the permissible limits for auxiliary devices normally installed on electrical wiring systems associated with these engines.

TABLE 6-3.

OTHER RFI/EMI SPECIFICATIONS (Cont.)

MIL-No.	TITLE	Mandatory Use by	Scope
I-16910C	INTERFERENCE MEASUREMENT, ELECTROMAGNETIC, METHODS AND LIMITS	Navy	Superseded by MIL-STD-461 and MIL-STD-462.
I-17623A	INTERFERENCE MEASUREMENT, ELECTROMAGNETIC; METHODS AND LIMITS, FOR ELECTRIC OFFICE MACHINES, PRINTING AND LITHOGRAPHIC EQUIPMENT	Navy	Superseded by MIL-STD-461 and MIL-STD-462.
STD-285	ATTENUATION MEASUREMENTS FOR ENCLOSURES, ELECTROMAGNETIC SHIELDING, FOR ELECTRONIC TEST PURPOSES, METHOD OF	Army, Navy, Air Force	This standard covers a method of measuring the attenuation characteristics of electromagnetic shielding enclosures used for electronic test purposes.

Defense has become aware of this problem, and at the time of issue of this handbook, MIL-STD-461, MIL-STD-462, and MIL-STD-463 are to take precedence over the other RFI/EMI specifications.

6-4.1 MIL-B-5087B

6-4.1.1 Bonding Surface Preparation

Surface preparation for an electrical bond shall be accomplished by removing all anodic film, grease, paint, lacquer, or other high-resistance properties from the immediate area to insure negligible radio frequency (RF) impedance between adjacent metal parts. Abrasives which cause corrosion, if embedded in the metal, shall not be used. If abrasives or scrapers are used to remove any protective finish, they shall be of such a nature that produces a clean, smooth surface without removing excessive material under the protective finish. Chemical cleaning and surface preparation shall be in accordance with standard practice.

6-4.1.2 Classes of Application

Electrical bond classes of application shall be as specified in Table 6-4.

TABLE 6-4

ELECTRICAL BOND CLASSES OF APPLICATION

Class	Application
A	Antenna installation
C	Current path return
H	Shock hazard
L	Lightning protection
R	RF potentials
S	Static charge

Where a single bond is used to serve two or more classes of application, the design shall conform to the most critical requirement of bonding.

6-4.1.2.1 Class A Bonding (Antenna Installations)

a. *Return path.* Antennas, so designed that efficient operation depends on low resistance, shall have the bond installed so that RF currents flowing on the external surface of a vehicle will have a low-impedance path of minimum length to the appropriate metal portion of the antenna.

b. *Coaxial antenna.* Provisions shall be made for circumferential (360° connection) RF continuity between outer conductors of coaxial antenna transmission lines and ground planes of antennas.

6-4.1.2.2 Class C Bonding (Current Path Return)

a. *Current capacity.* The bond between equipment and vehicle structure should not be used as a ground return in Army systems, rather a return wire or cable should be used. Table 6-5 shows the size of cable recommended.

b. *Voltage drop.* The total impedance of wires and cables shall be such that the voltage drop between the point of regulation and the load does not exceed the limits shown in Table 6-6. For current return leads of size AN-4(AWG-4), or larger wire, the bonding connection shall not be made directly to a structure but shall be made to a tab of sufficient size that is properly attached to the structure.

6-4.1.2.3 Class H Bonding (Shock Hazard)

a. *Resistance.* Metallic conduit-carrying electrical wiring shall have a low-resistance bond of less than 0.1 Ω to structure at each terminating and break point. The bonding path may be through the equipment at which the conduit terminates.

b. *Grounding.* Exposed conducting frames or parts of electrical or electronic equipment shall have a low-resistance bond of less than 0.1 Ω to structure. If the equipment design includes a ground terminal or pin which is internally connected to such exposed parts, a ground wire connection to such terminal or pin shall be provided. (Once again it should be noted that this is for shock protection and not a current return.)

6-4.1.2.4 Class L Bonding (Lightning Protection) (Except for Antenna Systems)

Lightning protection shall be provided at all possible points of lightning entry into the aircraft (or in this situation, any missile system). The entry points include but are not limited to the following:

a. Navigation lights

b. Fuel filler caps

c. Fuel gage covers

d. Refueling booms

e. Fuel vents

f. Antennas.

The bonding requirements which follow are designed to achieve protection against lightning discharge

TABLE 6-5

CURRENT-CARRYING CAPACITY OF WIRES AND CABLES

Wire or cable size		Continuous-duty current - A	
Aluminum	Copper	Single wire in free air	Wires and cables in conduit or bundles
	AN-22	--	5
	AN-20	11	7.5
	AN-18	16	10
	AN-16	22	13
	AN-14	32	17
	AN-12	41	23
	AN-10	55	33
	AN-8	73	46
	AN-6	101	60
	AN-4	135	80
	AN-2	181	100
	AN-1	211	125
	AN-0	245	150
	AN-00	283	175
	AN-000	328	200
	AN-0000	380	225
AL-8		60	36
AL-6		83	50
AL-4		108	66
AL-2		152	82
AL-1		174	105
AL-0		202	123
AL-00		235	145
AL-000		266	162
AL-0000		303	190

TABLE 6-6

SYSTEM VOLTAGES AND ALLOWABLE VOLTAGE DROPS

Nominal system voltage	Maximum allowable voltage drop	
	Equipment operation	
	Continuous	Intermittent
28	1	2
115	4	8
200	7	14

current carried between the extremities of an airborne vehicle without risk of damaging flight controls or producing sparking or voltages within the vehicle in excess of 500 V. These requirements are based upon a lightning current waveform of 200,000 A, peak; a width of 5 to 10 μsec at the 90-percent point; not less than 20 μsec width at the 50-percent point; and a rate of rise of at least 100,000 A/μsec.

a. *Size of conductor.* Individual bonding jumpers for lightning protection shall be not less than No. 12 AWG for tinned stranded copper wire or No. 10 AWG for stranded aluminum wire. These wire sizes are valid only when a minimum of two jumpers are installed to carry the lightning current and when the jumpers are not subject to a direct arc. When the jumpers may be subject to arcing, substantially larger wire sizes 40,000 circular mils (AWG-4) minimum are required for protection against multiple strokes.

b. *Soldered connections.* Soldered connections shall not be used on jumpers that are required to carry lightning currents.

c. *Bonding conductor restrictions.* Conductors shall be equal to, or larger than, 6,530 circular mils (AWG-12) for copper or 10,380 circular mils (AWG-10) for aluminum, where the conductor will not be subject to arcing. Where the conductor is subject to arcing, a minimum of 20,820 mils (AWG-7) for copper, or 33,100 mils (AWG-5) for aluminum, shall apply.

d. *Riveted skin construction.* Close riveted skin construction which divides any lightning current over a number of rivets is considered adequate to provide a lightning discharge current path.

6-4.1.2.5 Class R Bonding (RF Potentials)

a. *Grounding.* All electrical and electronic units or components which produce electromagnetic energy shall be installed to provide a continuous low-impedance path from the equipment enclosure to the structure. The contractor shall demonstrate by test that his proposed method results in a direct current impedance of less than 2.5 mΩ from enclosure to structure. The bond from the equipment enclosure to the mounting plate furnished with the equipment shall comply also with these requirements, except that suitable jumpers may be used across any necessary vibration isolators.

b. *Nearby conductors.* All conducing items having any linear dimension of 12 in. or more installed within 1 ft of unshielded transmitting antenna lead-ins shall have a bond to structure. Direct metal-to-metal contact is preferred. If a jumper is used, the jumper shall be as short as possible.

c. *Vehicle skin.* Vehicle skin shall be so designed that a uniform low-impedance skin is produced through inherent RF bonding during construction. RF bonding must be accomplished between all structural components comprising the vehicle; i.e., wings, fuselage, etc. Hatches, access doors, etc., not in the proximity of interference sources or wiring shall be either bonded to or permanently insulated from vehicle skin, except for the protective static bond. Consideration shall be given to the design to operational vibration and resultant breakdown of insulating finished or intermittent electrical contact.

6-4.1.2.6 Class S Bonding (Static Charge)

All isolated conducting items (except antennas) having any linear dimension greater than 3 in.–which are external to the vehicle, carry fluids in motion, or otherwise are subject to frictional charging–shall have a mechanically secure connection to the vehicle structure. The resistance of the connection shall be less than 1 Ω when dry.

6-4.2 MIL-I-6181D

6-4.2.1 Susceptiblity

The equipment shall be designed to minimize susceptibility to interference from other sources. The enclosing case construction shall be designed not only to minimize interference propagation, but also to minimize interference pickup from external sources. Where conducted energy on the power leads or any external leads might cause interference, the leads shall be isolated from other leads to avoid coupling and, where necessary, shall have line filters at their entry into the enclosing case. Receiving antenna imputs, or any other low-level signal circuits shall be low impedance, or of balanced design, so that coaxial or other shielded transmission lines can be used to insure an interference-free installation. Routing of receiving antenna input or any low-level signal circuit within the equipment shall be so designed and installed that interference is not picked up from power or control leads owing to common conductive paths with other circuits, or with enclosing case grounding path.

6-4.2.2 Case Shielding

The number of mechanical discontinuities in the case (such as covers, inspection plates, and joints) shall be kept to a minimum. All necessary mechanical discontinuities in the case shall be electrically continuous across the interface of the discontinuity so as to provide a low impedance current path. Multiple-point spring-located contacts are suggested as a desirable method of obtaining low impedance continuity. Ventilation openings shall be designed to permit conformance to the

radiated interference limits. Electrical bonding shall be provided where access doors or cover plates form a part of the shielding. Hinges, in themselves, are not considered satisfactory conductive paths.

6-4.2.3 Chassis, Case, and Mounting Continuity

The mating surface of the chassis, case, and mounting shall be free of all insulating finishes in order to provide a continuous electrical bond between these items and to enable the installing activity to accomplish bonding contact to the basic structure. Such surfaces shall be covered with removable protective coating to prevent corrosion prior to assembly. This requirement shall take precedence over any conflicting requirements in specifications on finishes.

6-4.2.4 Component Placement

Components shall be placed and circuitry arranged to obtain minimum undesired coupling and to require a minimum number of filter components.

6-4.2.5 Line Shielding

It is preferred that interference reduction be accomplished inside the equipment when such means give results equal to or better than the use of a shielded line. Any line shielding used shall be approved by the procuring activity and shall be prescribed as an installation requirement.

Under no condition shall line shielding be used for primary power leads to equipment.

Equipment requiring antennas, but not employing waveguides, shall be designed to utilize shielded coaxial cable as lead-in. When it has been determined that a single braid shield is not adequate, a double or triple braid or a solid shield shall be used as required.

6-4.3 MIL-P-24014

6-4.3.1 Firing Circuits

Firing circuits to EED's shall be electrically balanced to and isolated from the EED case and other conducting parts of the weapon. If some part of a firing circuit must be grounded or connected to a common power supply, there shall be only one such grounding point or interconnection with other electrical circuits. However, static-discharge resistors of not less than 100 kΩ may be connected to firing circuit conductors at any point where the application requires.

The conductors of the firing circuit shall be twisted to maintain electrical balance.

6-4.3.2 Attenuation

Equipment, weapon, or system enclosures shall attenuate RF energy by at least 60 dB from 1 MHz to 20 GHz. From 1 MHz the attenuation requirement may be diminished linearly to 40 dB at 100 kHz. The enclosure shall be constructed of material which provides good electromagnetic shielding. Environmental levels of field strengths and power densities are given in Table 6-7. When necessary to provide the required attenuation, each conductor which penetrates the enclosure shall be provided at its point of entry with a feed-through low-pass filter which meets the requirements of MIL-F-15733 appropriate to the specific application. Insertion loss of the filter shall at least equal the insertion loss characteristic *K* of MIL-F-15733. To assist in obtaining the required degree of shielding, the following features are required:

a. Each mechanical discontinuity in any shield shall be electrically continuous across the interface so as to provide low-impedance current paths. Multiple-point, spring-loaded contacts, or knitted-wire gaskets are recommended. Hinges and bonding wires are not considered satisfactory conductive paths.

b. There should be no holes or gaps in the shields exceeding 1/4 in. in greatest diameter. The number of holes with diameters less than 1/4 in. shall be held to a minimum. No unshielded conductor shall be located within one inch of any hole having a depth of less than 1 in.

c. EED firing circuits shall be isolated from each other and from other circuits by means of individual shields. Shielded EED firing circuits may be routed together in a common shield.

d. Metallic shields for firing circuit leads and other conductors shall be connected to the EED shield throughout its entire periphery to form a continuous shield without electrical discontinuities or gaps.

e. Mating connectors shall provide a shield which is electrically continuous through the connector and completely surrounds the conductor pins without any gaps. This shield shall not be used as a return circuit.

6-4.3.3 System Design

The following features are required for system shielding:

a. All sections of an assembled weapon and their skins shall be in good electrical contact with each other. Mating surfaces shall be free of insulating coatings or film. Such surfaces shall be of corrosive resistant materials or shall be covered with strippable protective coating to prevent corrosion prior to assembly.

TABLE 6-7

ENVIRONMENTAL LEVELS

Frequency, MHz	Electric Field, V/m	Average Power Density, W/m^2
Communications Equipment (continuous wave, unmoldulated carrier values)		
0.25 - 0.535	300	239
2 - 32	100	26
100 - 156	239	1
225 - 400	26.5	1
Radar Equipment		
200 - 225	194	100
400 - 450	61	10
1000 - 1300	61	10
2700 - 3600	194	100
5400 - 5900	614	1000
8500 - 10300	614	1000

b. EED systems, including firing circuits, shall be mechanically isolated as much as possible from other electrical devices and circuits and in no event shall the firing circuits be cabled with other circuits, except as may be necessary at a weapon/aircraft system interface.

c. Access doors which penetrate the weapon shield shall be held at a minimum. Such doors, when closed, shall provide reliable continuity of the shield for the EED's. The system design should not require such doors to be opened while the system is located in electromagnetic fields of the magnitude indicated in Table 6-6 unless, when so doing, the system will continue to not be adversely affected by opening such doors.

d. There shall be no more than one cable connecting weapons to other structures. This cable shall be shielded and as short as practicable with the shield connected to the external surface of the weapon or equipment case or frame. Shield connections shall completely surround the cable, without gaps. The cable shall be provided with connectors designed to completely mate with the outer shell (shield) surface before any of the inner conductors make contact; and when being unmated, shall completely open circuit all conductor pins before the shell (shield) contact surface has broken contact. The pins on the inner conductors of the portion of the connector toward the EED shall be female and recessed into the insulator to prevent unintentional contact by fingers or tools. In addition, the tips of the female pins shall be recessed well below the lip of the surrounding shield to provide additional shielding. A metal cap shall be provided for the connector on the EED side for installation when the weapon is not in use.

e. Grounding of the weapon shall be in accordance with MIL-B-5087, Class R bonding. Provisions shall be made to electrically bond the weapon case directly to its launcher or other component.

f. Weapon-launcher system design shall provide convenient and easy connection of the cable between weapon and launcher after the weapon case has made good electrical contact with the launcher. Protective coatings applied to the launcher or weapon shall not prevent good electrical continuity at contacting surfaces.

6-4.4 MIL-STD-833

a. EED firing circuits will be isolated from other circuits and each other by means of individual shields.

Shielded EED circuits may be routed together in a common secondary shield.

b. Circuits to EED's will be balanced to and isolated from the EED case and other conducting parts of the weapon. If a circuit must be grounded, there will be only one interconnection with other circuits. Static discharge resistors of 100,000 Ω or more may be connected to firing circuits.

c. Firing circuit conductors will be twisted to maintain electrical balance and reduce induction.

d. Firing circuit wiring will be kept to a minimum.

e. All conductors that connect the EED with other weapon components will be provided with metallic shields to provide an integral shield without electrical discontinuities or gaps.

f. Connectors will be kept to a minimum. Connector construction will be such that, when being mated, the shield contacting surfaces will mate before any of the inner conductors and will not break contact until after all inner conductors have broken contact. Also, the inner conductors of the connector on the EED side will be recessed in the shield opening.

g. Wiring within an EED will be isolated from any metallic case or enclosure. The impedance to case from each conductor will be equal and high as practicable.

APPENDIX A

DERIVATION OF THE GENERAL SHIELDING EFFECTIVENESS FORMULA

A relatively easy solution to a shielding problem is available if both the shield and the incident field exhibit rectangular, cylindrical, or spherical symmetery. Fig. A-1 illustrates the simplest of these configurations in section. Here the incident wave impinges normally on the solid metal shield of thickness t. The shield is assumed to extend to infinity and thereby divides space into two separate volumes. It should be noted that all solid shields divide space into two volumes; one containing the electromagnetic source (or assumed incident field), and a second the point at which the field reduction due to the insertion of the shield is to be calculated. Shielding that has large holes or otherwise fails to completely separate the incident field from the field calculation point usually presents more difficulty.

The field incident on the shield is assumed to be a function of the z coordinate only, and the individual electric and magnetic field components are assumed to be perpendicular to each other in the xy-plane. A wave of this type is termed a plane wave. Plane waves are the easiest dynamic solution to Maxwell's equations and will be the main concern in shielding problems. In free space, the electromagnetic field will propagate in every direction away from the source; thus, in any limited portion of space the fields show a spherical shape. At large distances from the source, a finite portion of the surface of this sphere is a plane, and the fields are plane waves. Strictly speaking, no perfectly plane wave can be produced in practice due to the effects of other bodies in space, but many actual fields approximate plane waves so well that present measurement techniques show no difference.

The solution of Maxwell's equations for the geometry of Fig. A-1 consists of a pair of electromagnetic fields, traveling in the $+z$ and $-z$ directions, in each of the volumes A, B and C. For this particular problem the wave traveling in the $-z$ direction in volume C has zero magnitude and can be ignored; this results from assuming that volume C extends infinitely in the $+z$ direction. The electromagnetic field traveling in the $+z$ direction in volume A will be called the incident field and is the field that would exist at point P (a measurement point in volume C) if the shield were absent.

The magnitude and phase of the remaining fields are determined, in terms of the incident field, by the electromagnetic properties of the materials filling volumes A, B, and C and the thickness of B. The mathematical procedure for determining the remaining fields involves matching the fields at the volume interfaces so that the electromagnetic boundary conditions implicit in Maxwell's equations are satisfied. For the geometry of Fig. A-1 there is an exact analog of the electromagnetic field equations in the more familiar transmission line equations. Use of the transmission line equations will help to systematize the matching of the various electromagnetic fields at the interfaces. If we adapt the transmission line variables to this problem, the total reduction of the electric or magnetic field strength at point P, due to the insertion of the shield (volume B in Fig. A-1), can be calculated from

$$\left|\frac{\text{Field (Shield Present)}}{\text{Field (Shield Absent)}}\right| = \left|\tau_{in}\exp\left[-\gamma_s t\right]\tau_{out}\right| \quad \text{(A - 1)}$$

where t is the thickness of the shield, γ_s is a function of the shield's electrical parameters, and the τ's, or transmission coefficients, are defined at each interface in the problem. The vertical lines denote the magnitude of the probably complex enclosed quantity.

The electrical parameters of the shielding medium that are needed for a numerical solution in terms of the transmission line variable formulation are:

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)}\text{ , meters, the propagation constant of the medium}$$

$$Z = R + jX = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}}\text{ ohms, the intrinsic impedance of the medium} \quad \text{(A-2)}$$

where

ω = angular source frequency ($2\pi f$)
μ = permeability of medium
σ = conductivity of medium

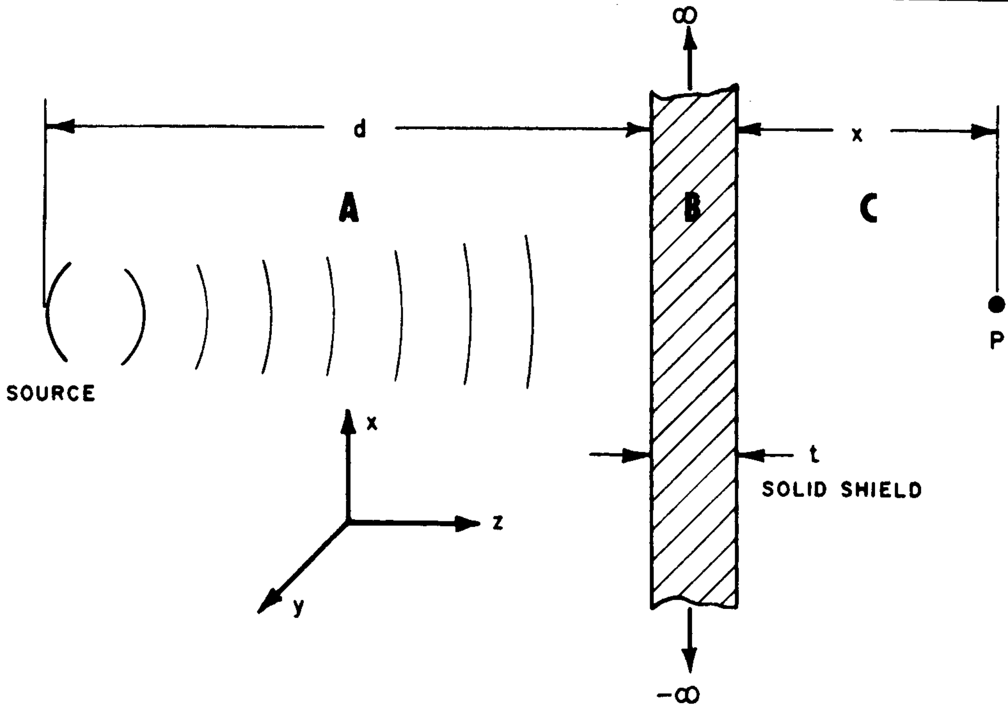

Fig. A-1. Geometric Representation of a Practical Shielding Problem

ϵ = permittivity of medium

f = frequency in hertz

It must be remembered that the electromagnetic properties–μ, σ, ϵ–are functions of the frequency f. These parameters, as indicated above, are generally complex quantities. α, the real part of the propagation constant γ, is the attenuation constant; β, the imaginary part of γ, is the phase constant. The square roots in Eq. A-2 are chosen such that they result in a positive real part, thus making the results consistent with the usual, though arbitrary, interpretation.

For free space–and as an excellent approximation for air–$\sigma = 0$, $\mu = 4\pi \times 10^{-7}$ H/m, and $\epsilon = 8.85 \times 10^{-12}$ F/m. After making these substitutions the following values are obtained:

$$\gamma_A = j\left(\frac{2\pi f_{MHz}}{300}\right), \text{ m}^{-1} \qquad \text{(A-3)}$$

$$Z_A = 377, \ \Omega$$

where f_{MHz} is frequency in megahertz.

For metals, and hence for the shield, the conductivity σ is much larger than the $\omega\epsilon$ product for all frequencies likely to be encountered. For example, a metal that is 100 times less conductive than copper (whose ϵ is equal to that of free space) will still have a conductivity at least one hundred times the $\sigma\epsilon$ product for all frequencies up to approximately 100 MHz. In consequence, values for the shield are:

$$Z_s = R_s + jX_s = (1+j)\sqrt{\frac{\omega\mu_s}{2\sigma_s}}$$

$$= (1+j)2.61\text{x}10^{-4}\sqrt{\frac{\mu_r f_{MHz}}{G_R}}, \ \Omega$$

and

$$\gamma_s = \alpha_s + j\beta_s = (1+j)\sqrt{\frac{\omega\mu_s\sigma_s}{2}} \qquad \text{(A-4)}$$

$$= (1+j)0.384\sqrt{\mu_r f_{MHz} G_R}, \text{ mils}^{-1}$$

where μ_r is the permeability of the shield in relation to free space and G_R is the conductivity of the shield in relation to annealed copper.

The transmission coefficient (dimensionless) at any interface is given by

$$\tau = \frac{2Z_t}{Z_I + Z_t} \qquad \text{(A-5)}$$

where Z_I is the intrinsic impedance of the medium on the source side of the interface and Z is the impedance seen looking into the medium on the side away from the source. The impedance looking into a medium is given by

$$Z_{in} = Z_o \left(\frac{Z_L + Z_o \tanh \gamma_o t}{Z_o + Z_L \tanh \gamma_o t} \right), \text{ ohms} \quad \text{(A-6)}$$

where Z_{in} is the "input" impedance of a medium with intrinsic impedance Z_o, propagation constant γ_o, and thickness t. This medium in turn is terminated with another medium which has an "input" impedance Z_L.

Note that Eq. A-6 will equal Z_o if the real part of $\gamma_o t$ is large because this forces $\tanh \gamma_o t$ to approach a limit of 1.

For the problem specified in Fig. A-1, the transmission coefficient at the shield interface away from the source field is

$$\tau_{out} = \frac{2Z_A}{Z_s + Z_A} \quad \text{(A-7)}$$

where Z_s is the intrinsic impedance of the shield and Z_A is the intrinsic impedance of air. The transmission coefficient at the source side of the shield is

$$\tau_{in} = \frac{2Z_{in}}{Z_A + Z_{in}} \quad \text{(A-8)}$$

$$= \frac{2Z_s (Z_a + Z_s \tanh \gamma_s t)}{Z_A (Z_s + Z_A \tanh \gamma_s t) + Z_s (Z_A + Z_s \tanh \gamma_s t)}$$

where Z_{in} is computed from Eq. A-6 using $Z_o = Z_s$, $Z_L = Z_A$ and $\gamma_o = \gamma_s$.

The total field reduction expressed in dB is given by 20 log of Eq. A-1, using the above expressions for transmission coefficients. Inverting the expression to obtain a positive value for dB,

$$dB_{loss} = 20 \log \left| e^{\gamma_s t} \frac{(Z_s + Z_a)}{4Z_s Z_A} \right. \quad \text{(A-9)}$$

$$\left. \left[\frac{Z_A (Z_s + Z_A \tanh \gamma_s t) + Z_s (Z_A + Z_s \tanh \gamma_s t)}{Z_A + Z_s \tanh \gamma_s t} \right] \right|$$

This formula is the basis for most far-field shielding effectiveness calculations. If the real part of $\gamma_s t$ is sufficiently large, $\tanh \gamma_s t$ approaches 1 and the equation reduces to

$$dB_{loss} = 20 \log \left| e^{\alpha_s t} \frac{(Z_A + Z_s)^2}{4Z_A Z_s} \right| \quad \text{(A-10)}$$

Fig. A-2 plots the magnitude and phase of tanh $\gamma_s t$ for selected values of $\alpha_s t$, and indicates that Eq. A-10 should be accurate to a few percent if $\alpha_s t$ is larger than 2.

Fig. A-3 plots, as a function of frequency, the shield thickness required, for nonmagnetic metals of various conductivities, to have $\alpha_s t$ equal to 2. The relative permeabilities (at 150 kHz) of various metals are given in Table 4-3.

In general most common metals that are used for shielding (copper, aluminum, etc.) have an $\alpha_s t$ product which is greater than 2 at frequencies above 1 MHz, provided the shield is thicker than 20 or 30 mils. This is convenient since it is usually necessary to make a shield at least this thick in order to make it self-supporting.

If the magnitudes of the intrinsic impedances of air and typical metal shields are compared (Eqs. A-3 and A-4), it becomes evident that the magnitude of the shield's intrinsic impedance will be very much smaller than that for air at all frequencies below 10^5 MHz. Incorporating $Z_s << Z_A$ in Eq. A-10, total loss will be, to a very good approximation,

$$dB_{loss} = 20 \log \left| e^{\alpha_s t} \frac{Z_A}{4Z_s} \right| = 3.34 \left(\sqrt{f_{MHz} \mu_r \sigma_r} \right) t$$

$$- 10 \log \left(\frac{f_{MHz} \mu_r}{\sigma_r} \right) = 108.2 \quad \text{(A-11)}$$

where the thickness of the shield t is in mils.

A more practical shielding example for the same geometry is shown in Fig. A-4. Consider an impinging field that, although it is propagating through air, has a general wave impedance of Z_w. Incident fields of impedance different than Z_A are found close to sources and may also be created by reflection from objects near the shield even if the shield is far from the source. In Fig. A-4 an impedance is also associated with the measurement point. This impedance Z_ℓ must be considered as different from Z_A since we are now considering an object inserted into the protected volume that we previously considered as extending indefinitely. This problem can be treated by the same transmission line techniques that we used earlier. The general result is (Ref. 1):

$$\frac{\text{Field}_p \text{ [Shield Present]}}{\text{Field}_A \text{ [Shield Absent]}} = \frac{2Z_s (Z_w + Z_\ell) e^{-\gamma_s t}}{(Z_w + Z_s)(Z_s + Z_\ell)}$$

$$\left[1 - \frac{(Z_w - Z_s)(Z_\ell - Z_s)}{(Z_w + Z_s)(Z_s + Z_\ell)} e^{-2\gamma_s t} \right]^{-1} \quad \text{(A-12)}$$

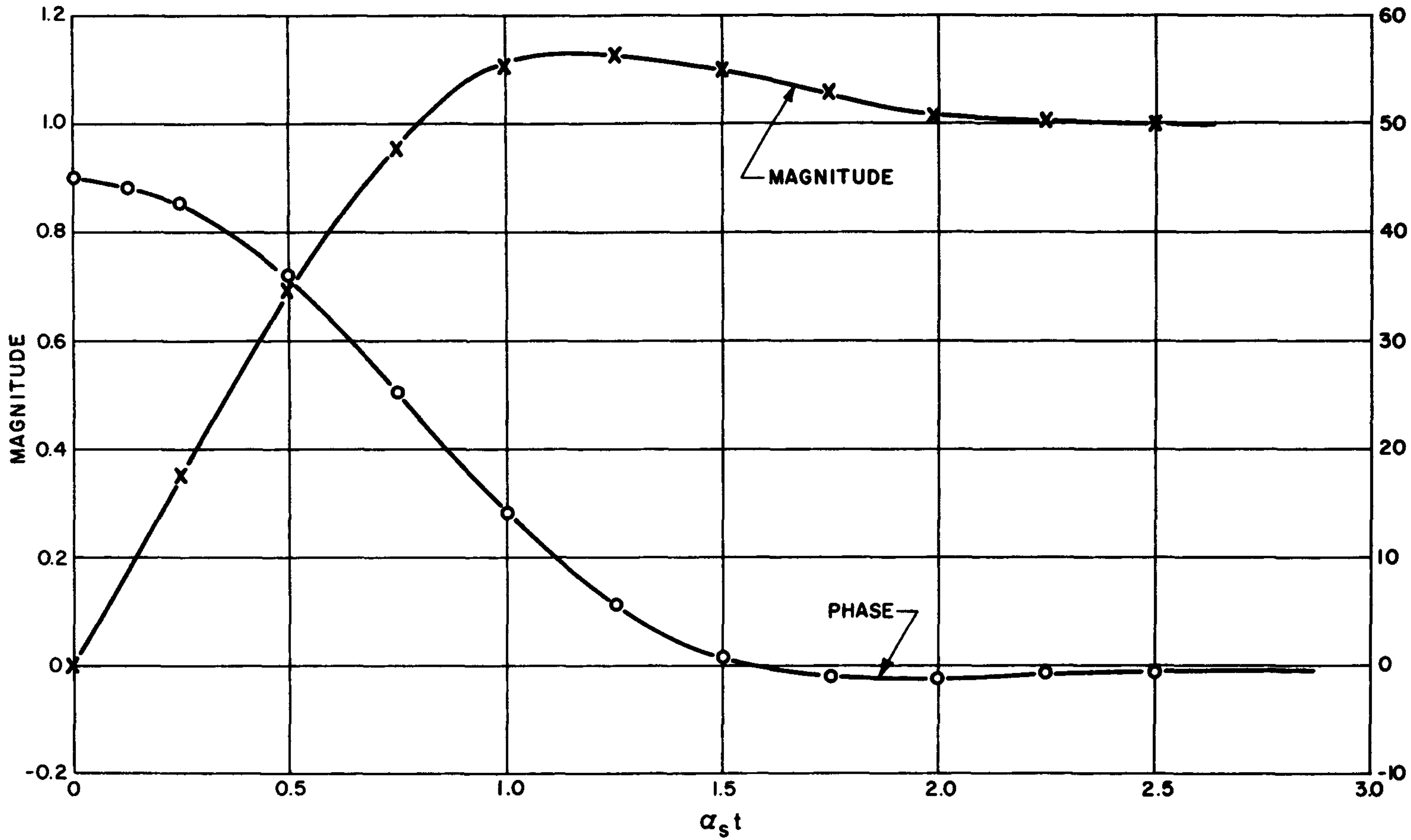

Fig. A-2. Magnitude and Phase Angle of tanh $(\gamma_s t)$ for Various Values of $\gamma_s t$ When $\gamma_s t = \alpha_s t(1 + j)$

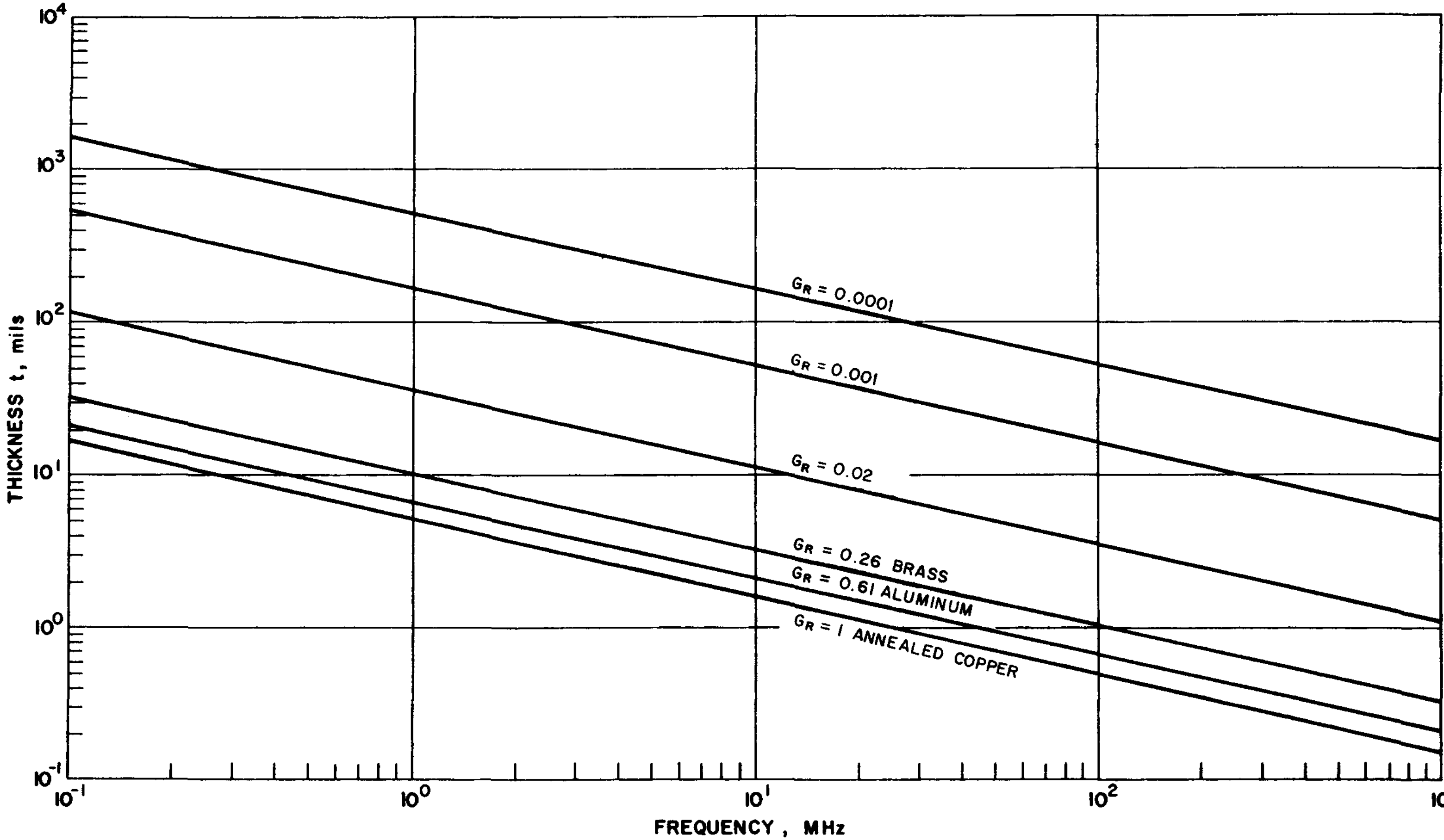

Fig. A-3. Thickness Required for $\alpha_s t = 2$

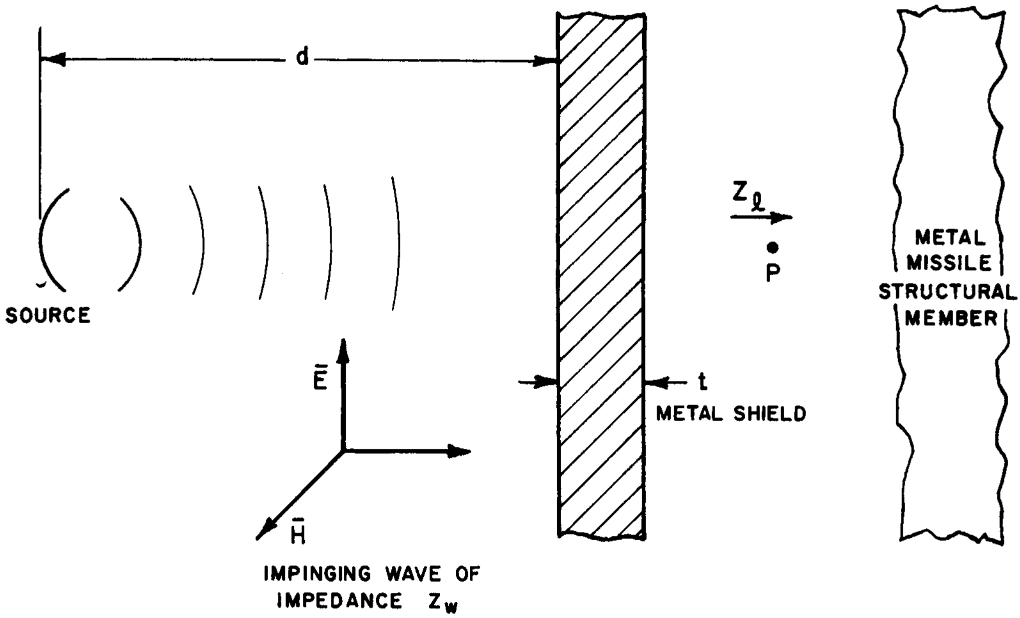

Fig. A-4. A Practical Shielding Problem

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GLOSSARY

A

absorption. Transfer of electromagnetic wave energy to a substance being traversed by the wave.

antenna array. A system of antenna elements arranged to obtain the desired directional radiation pattern.

antenna field. *See:* **antenna pattern.**

antenna pattern. A diagrammatic representation of the radiation field from an antenna, usually in terms of loci representing equal power levels.

arming. 1. The technique of completing the firing signal transfer path through the safing and arming device. 2. The changing from a safe condition to a state of readiness for functioning.

arming device. Device for arming of a fuze under controlled conditions.

arming system. *See:* **safing and arming mechanism or device.**

B

balanced circuit. A circuit having its two sides electrically alike and symmetrical with respect to a common reference point, usually ground.

bond. An electrical connection between metal parts of a structure.

bonding. A system of connections between metal parts of a system forming a continuous electrical unit.

braided shield. The woven multi-strand electrically conductive shield enclosing a cable of insulated wires.

breakdown. Disruptive electric discharge through insulation on wires, insulators, or other materials separating circuits.

breakdown voltage. The voltage at which an insulating material ceases to insulate and becomes electrically conductive.

C

chassis. The metallic base on which the parts of electronic circuits are mounted.

circuit component. One of the simple parts of the whole complex circuit.

circuit element. *See:* **element.**

compatibility. A characteristic ascribed to the overall system with reference to how well its various subsystems work together.

conductor. A wire, cable, or other material which will freely permit the passage of an electric current, when a difference of potential is applied.

corona discharge. A luminous, electrical discharge caused by ionization of air surrounding a high voltage conductor.

D

dart leader. A charge column extending from earth to cloud that precedes all strokes other than the first.

decibel (dB). A dimensionless measure of the ratio of two powers, equal to ten times the logarithm to the base ten of the ratio of the two powers.

detector. A device to sense presence or change in some environmental condition.

detonator. An explosive device initiated by electrical or mechanical means.

diathermy. The therapeutic heating of tissues beneath the skin by means of high-frequency electrical oscillation; also, the apparatus used.

dipole. A combination of the two electrically or magnetically charged particles of opposite sign which are separated by a very small distance.

dipole antenna. A straight radiator, usually fed in the center, and producing a maximum of radiation in the plane normal to its axis. The length specified is the overall length.

displacement current. The current which is proportional to the time rate of change of electric displacement flux through any surface in an isotropic dielectric.

dissipation. The loss of energy through resistive forces, which ultimately appear as heat loss.

duty. A requirement of electric power supply service which defines the degree of regularity of the load.

duty cycle. The ratio of the on time interval to the total time of one operating cycle.

E

electroexplosive device (EED). An explosive device that is initiated by an electric stimulus. See Table 4-1 for the specific types of EED's.

electromagnetic compatibility (EMC). The ability of a system of electrical components to operate properly and without degredation despite the coupling of spurious electrical stimuli between them.

electromagnetic environment. The RF field or fields existing at a specific place.

electromagnetic interference (EMI). The designation for all unwanted voltages or currents resulting from unwanted electromagnetic fields that tend to impair equipment performance.

electromagnetic pulse (EMP). The electric and magnetic fields (energy) propagating from a nuclear explosion.

electromagnetic spectrum. The ordered array of known electromagnetic radiations, extending from the shortest cosmic rays through gamma rays, X-rays, ultraviolet radiation, visible radiation, infrared radiation, and including microwave and all other wavelengths of radio energy.

electrostatic. Relating to, possessing, or employing electric charges and their characteristics.

electrostatic induction. The mechanism by which a body becomes charged when it approaches a charged body, and before physical contact is established between them.

element. Any electrical device (such as inductor, resistor, capacitor, line) with terminals at which it may be directly connected to other electrical devices.

environment. An external condition in which a piece of equipment or system operates.

F

field intensity. *See:* **field strength.**

field strength. For any physical field, the flux density, intensity or gradient of the field at the point in question (magnitude of the field vector).

filter. A term widely applied to many kinds of devices that permit selectively the passage of only certain frequencies.

flux. The rate of transferring energy across a given surface.

fuse. A protective device, used in an electric circuit, containing a wire, bar, or strip of fusible metal. When the current increases beyond the rated strength of the fuse, the metal melts and thus the circuit is broken.

fuze. A device designed to initiate a detonation under desired conditions.

G

gain. A general term to denote an increase in signal power in transmission from one point to another.

grid. Pertaining to or measured from a reference line.

ground. A conducting connection between an electric circuit or equipment and earth, or to some conducting body which serves in place of the earth.

ground loop. An undesired mutual coupling between circuits caused by equipment grounding methods.

guard ring. An auxiliary electrode used to control potential gradients, reduce insulator leakage, and to define the sensitive volume.

H

hardening. Protection against or decoupling from an external environment.

I

igniter. *See:* **electroexplosive device.**

incident. Falling or striking on a surface.

incident wave. A wave traveling through a medium which impinges on a discontinuity or a medium of different propagation characteristics.

induction. The act or process by which an object is electrified, magnetized, or given an induced voltage by exposure to a field.

initiation. The application of a fuze signal to the first elements of an explosive train.

initiator. *See:* **electroexplosive device.**

insertion loss. The ratio of received power before and after the insertion of shielding between a source and a receiver of electromagnetic energy.

insertion loss, transducer. The loss resulting from the insertion of a transducer in a transmission system, which is the ratio of the power delivered to that part of the system which will follow the transducer, before insertion of the transducer, to the power delivered to that same part of the system after insertion of the transducer.

interference. An extraneous signal which tends to disturb the reception of the desired signal, or the disturbance of signals which results.

ionization. The process by which neutral atoms become electrically charged, either positively or negatively, by the loss or gain of electrons.

irradiation. The exposure of material to radiation.

isotropic. In general, pertaining to a state in which a quantity or spatial derivatives thereof are independent of direction.

J

jumper. A short length of conductor used to complete an electrical circuit, usually temporary between terminals, or to bypass an existing circuit.

L

leader. A primary or terminal shoot of a lightning stroke.

load. The device which receives signal power from a source.

M

matching. The connecting of two circuits in such a way that the correct impedance exists in each circuit for maximum transfer of energy.

matching impedance. The technique of minimizing the standing-wave ratio when two devices having unlike impedances are coupled. This process maximizes power flow between the two devices.

mobile stations. A missile launch complex designed for mobile use in forward combat areas.

mode. A functioning position or arrangement that allows for the performance of a given task.

N

noise. That portion of the unwanted signal which is statistically random.

nuclear radiation. A pulse of neutrons and photons (X-ray and gamma ray energy band) radiating from a detonating nuclear weapon.

P

pigtail. A flexible metallic conductor, frequently stranded, attached to a terminal of a circuit component, and used for connection into the circuit.

pilot streamer. The initial cloud to ground discharge in a lightning stroke.

potential gradient. In general, the local space rate of change of any potential.

power density. The real part of the Poynting Vector at a point in space.

power rating. The power transfer or power dissipation capabilities.

propagation. The travel of waves through or along a medium.

pulse. A single disturbance of definite amplitude and time length, propagated as a wave of electric current.

R

radiation pattern. A graphical representation of the radiation of an antenna as a function of direction.

radiator. Any source of radiant energy, especially electromagnetic radiation.

radio energy. Electromagnetic radiation of wavelength greater than 0.01 centimeter.

radio frequency interference (RFI). Any interfering signal capable of being detected on a receiver tuned to a radio frequency.

radio interference. Any electrical noise which interferes with the reception of a desired signal.

rating. A designated limit of operating characteristics based on definite conditions.

reflection. The process whereby a surface of discontinuity turns back a portion of the incident radiation into the medium through which the radiation approached.

reflection loss. The part of the transmission loss due to the reflection of power at a discontinuity.

reflective attenuation. The loss of part of the power available to a matched load because of mismatch at the input and output terminals of an attenuator inserted between generator and load.

S

safing and arming mechanism or device (S&A). A switching device to mechanically interrupt the functional path between fuze and warhead until after proper launching has taken place; arming consists of completing the functional path at the proper time.

saturation. The state of being satisfied. Magnetic saturation is the maximum magnetization of which a body or substance is capable.

sensitivity. In general, the degree of response to external action.

shield. A bond of material used to prevent or reduce the passage of radiation or particles.

shorting cap. A device to provide a short circuit across an EED during storage, shipment, and handling.

signal. A visual, audible, or other indication used to convey information.

spectrum. Short for electromagnetic spectrum.

spectrum. A continuous wide range of frequencies

within which waves have some specified common characteristic, e.g., RF spectrum.

squib. *See:* **electroexplosive device.**

static electricity. A charge of electricity accumulated by an object, which charge creates a spark when the object comes near another object to which it may transmit its charge, or from which it may receive a charge.

subsystem. A major functional assembly within a system.

surge. A voltage or current of large magnitude and short duration (a transient rise) caused by an abrupt discontinuity in a circuit or system.

survivability. The ability of a device or system to perform its proper function during or following an adverse environment.

susceptibility. The lack of ability to resist external stimuli. The response (transfer function) of the device or system as a function of the interference level.

system. A major devision of a given network that performs one or more vital functions.

T

termination. A synonym for load.

thermal radiation. The electromagnetic radiation emitted by any substance as the result of the thermal excitation of its molecules.

thermal stacking. The increase in temperature of a device resulting from the application of repetitive pulses at a rate and magnitude exceeding its capabilities to dissipate the heat.

time constant. Generally, the time required for an instrument to indicate a given percentage of the final reading resulting from an input signal.

transient. That part of the forced oscillation of a linear system which decays more or less rapidly after the imposition of the force. The nonpermanent terms in the response of an electric network to a stimulus.

twisted pair. A cable composed of two insulated conductors twisted together either with or without a common covering.

U

unidirectional. Having only a single well-defined direction.

V

vulnerability. The openness of a target to a damage agent. The threshold level above which the interference causes the device or system to malfunction during or following an adverse environment.

W

waveform. The graphical representation of a wave, showing variation of amplitude with time.

waveguide. A system of boundaries capable of guiding waves.

weapon system. A group of tactical devices which together perform a mission.

worst case attenuation. The minimum attenuation that a system can exhibit regardless of the system's impedance.

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Chapter 6

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2. *Electro-Interference Control Requirements for MINUTEMAN (WS-133B)*, Exhibit 62-87, Headquarters, Ballistic Systems Division, Air Force System Command, 6 December 1963. This document specifies standard of performance to be met, design requirements, and design guides for the MINUTEMAN weapon system.

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